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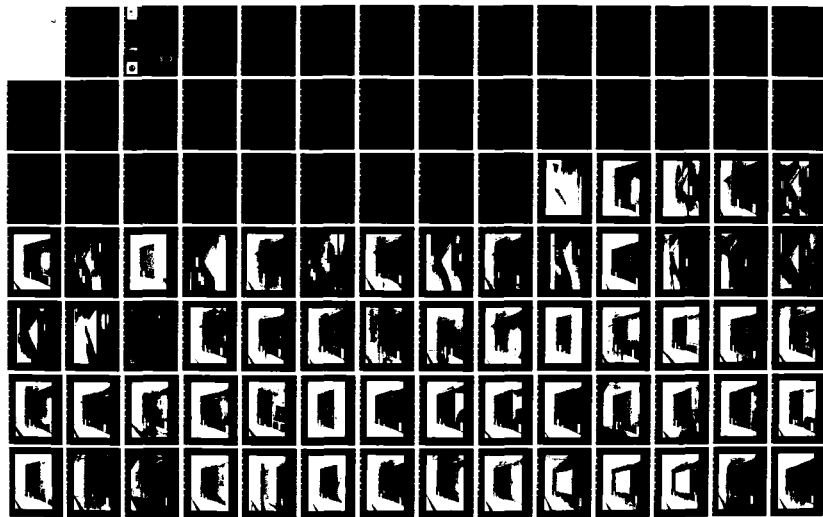
STABILITY OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND  
BREAKWATER TRUNKS SUBJ. (U) COASTAL ENGINEERING  
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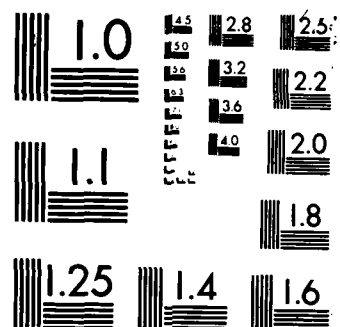
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TECHNICAL REPORT CERC-83-5



US Army Corps  
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# STABILITY OF STONE- AND DOLOS-ARMORED, RUBBLE-MOUND BREAKWATER TRUNKS SUBJECTED TO BREAKING WAVES WITH NO OVERTOPPING

by

Robert D. Carver

Coastal Engineering Research Center  
U. S. Army Engineer Waterways Experiment Station  
P. O. Box 631, Vicksburg, Miss. 39180



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Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The objective of the research presented is to furnish design information for stone and dolos armor on nonovertopping breakwater trunks that are subjected to severe depth-limited breaking waves. Since it would be a mammoth task to comprehensively investigate all the different types of existing armor, this particular research effort concentrated on stone and dolosse. Stone is a natural and economical protection when it is of sufficient size and quality to meet design constraints; and dolosse, according to nonbreaking (Continued)		

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20. ABSTRACT (Continued)

wave data, is the best hydraulically stable concrete armor unit. Results of this research indicate that both stone stability and dolos stability are critical relative to breaking waves, thus these breaking wave stability coefficients for breakwater trunks should be on the order of 2 and 15, respectively.

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## PREFACE

Authority for the U. S. Army Engineer Waterways Experiment Station (WES) to conduct this study, Work Unit No. 31269, "Stability of Breakwaters," Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development, was contained in a letter from the Office, Chief of Engineers (OCE), U. S. Army, dated 19 May 1972. OCE Technical Monitors for this research were Messrs. J. H. Lockhart, CDR USACE (DAEN-CWH-D), J. G. Housley, CDR USACE (DAEN-CWP-P).

The study was conducted by personnel of the Hydraulics Laboratory, WES, under the general direction of Messrs. H. B. Simmons and F. A. Herrmann, Jr., Chief and Assistant Chief of the Hydraulics Laboratory; Dr. R. W. Whalin and Mr. C. E. Chatham, former and present Chief of the Wave Dynamics Division, and Mr. D. D. Davidson, Chief of the Wave Research Branch. The Wave Dynamics Division and its personnel were transferred to the Coastal Engineering Research Center (CERC) of WES on 1 July 1983 under the direction of Dr. Whalin, Chief of CERC. Tests were planned by Mr. R. D. Carver, Project Engineer, and Mr. W. G. Dubose, Engineering Technician. The model was operated by Mr. Dubose under the supervision of Mr. Carver. This report was prepared by Mr. Carver.

Commander and Director of WES during the conduct of the study and the preparation and publication of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)  
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
feet per second per second	0.3048	metres per second per second
inches	25.4	millimetres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

STABILITY OF STONE- AND DOLOS-ARMORED, RUBBLE-MOUND BREAKWATER  
TRUNKS SUBJECTED TO BREAKING WAVES WITH NO OVERTOPPING

PART 1: INTRODUCTION

Background

1. The experimental investigation described herein constitutes a portion of a research effort to provide engineering data for the safe and economical design of rubble-mound breakwaters. In this study, a rubble-mound breakwater is defined as a protective structure constructed with a core of quarry-run stone, sand, or slag and protected from wave action by one or more stone underlayers and a cover layer composed of selected quarrrystone or specially shaped concrete armor units.

2. Rubble-mound breakwaters are used extensively throughout the world to provide protection from the destructive forces of storm waves for harbor and port facilities. A proposed structure may necessarily be designed for either nonbreaking or breaking waves depending upon positioning of the breakwater and severity of anticipated wave action during its economic life. Some local wave conditions may be of such magnitude that the protective cover layer must consist of specially shaped concrete armor units in order to provide economic construction of a stable breakwater; however, many local design requirements are most advantageously met by quarrrystone armor. This particular report addresses the use of quarrrystone and dolos armor on breakwater trunks subjected to breaking waves.

3. Previous investigations have yielded a significant quantity of design information for quarrrystone (Hudson 1958 and Carver 1980) tetrapods, quadripods, tribars, modified cubes, hexapods, and modified tetrahedrons (Jackson 1968), dolosse (Carver and Davidson 1977), and toskane (Carver 1978). Although all of the above studies were important and filled a need, they were limited in that test waves were always nonbreaking. A few breaking wave tests are reported (Hudson 1961), but the breaking wave coefficients presented in the Shore Protection Manual (U. S. Army CERC 1977) were primarily developed from adjustments made to nonbreaking wave coefficients as supplemented by site-specific studies. A comprehensive study to develop general stability coefficients for depth-limited breaking waves has not previously been conducted.

### Purpose of Study

4. The purpose of the present investigation was to obtain design information for stone and dolos armor used on breakwater trunks and subjected to breaking waves. More specifically, it was desired to determine the minimum weight of individual armor units (with given specific weights) required for stability as a function of:

- a. Type of armor unit.
- b. Sea-side slope of the structure.
- c. Wave period.
- d. Wave height.
- e. Water depth.
- f. Sea-bottom slope on which the breakwater is constructed.

Also, it was desired to determine the magnitude of wave runup that can be expected for a selected range of incident wave conditions.

## PART II: DIMENSIONAL ANALYSIS

### Stability of Rubble-Mound Breakwaters

5. When short-period waves attack rubble-mound breakwaters, the interaction of the dislodging forces induced by the water motion and the resistive action of the armor units produce a complex dynamic phenomenon. Previous attempts to analyze this phenomenon to ascertain the magnitude of the dynamic forces involved by theoretical analyses have not been successful; however, coastal scale models/experimental tests of breakwaters can yield accurate design information that relates the required weight of individual armor units to breakwater geometry, local bathymetry, wave characteristics, etc.

6. An attempt will be made through the use of dimensional analysis to develop functional relationships between the primary variables affecting armor stability. Buckingham's  $\pi$  theorem can be used to determine the number of dimensionless and independent quantities (pi terms) required to express a relationship among the variables in any phenomenon. Dimensional analysis may then be used to obtain a suitable set of pi terms.

7. Definitions and characteristic dimensions in terms of force (F), length (L), and time (T)\* of the primary variables affecting armor stability are as follows:

$\gamma_a$  = specific weight of an armor unit,  $F/L^3$

$W_a$  = weight of an armor unit, F

$\Delta$  = shape factor of the armor unit, dimensionless

$\gamma_w$  = specific weight of water,  $F/L^3$

H = wave height, L

L = wavelength, L

d = water depth, L

g = acceleration due to gravity,  $L/T^2$

h = height of breakwater crown, L

$\beta$  = angle of wave attack, dimensionless

$\nu$  = kinematic viscosity,  $L^2/T$

$\alpha$  = angle between the horizontal and the seaward face of the breakwater, dimensionless

---

\* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

$\theta$  = angle between the horizontal and the sea bottom on which the breakwater is constructed, dimensionless

PT = technique used to place armor units in the cover layer, dimensionless

D = damage parameter, dimensionless

8. The present investigation addresses only waves normal to nonoverlapping breakwater sections. Therefore the variables  $\beta$  and  $h$  are eliminated. Also, since  $\alpha$  is directly related to the seaward slope of the breakwater, this variable can be replaced by  $\cot \alpha$  where  $\cot \alpha$  is the reciprocal of breakwater slope. With these considerations, the list of variables becomes

$\gamma_a$  = specific weight of an armor unit,  $F/L^3$

$W_a$  = weight of an armor unit, F

$\Delta$  = shape factor of the armor unit, dimensionless

$\gamma_w$  = specific weight of water,  $F/L^3$

H = wave height, L

L = wavelength, L

d = water depth, L

g = acceleration due to gravity,  $L/T^2$

$\nu$  = kinematic viscosity,  $L^2/T$

$\cot \alpha$  = reciprocal of breakwater slope, dimensionless

$\theta$  = angle between the horizontal and the sea bottom on which the breakwater is constructed, dimensionless

PT = technique used to place armor units in the cover layer, dimensionless

D = damage parameter, dimensionless

9. With 13 independent variables and 3 basic dimensions involved, Buckingham's  $\pi$  theorem predicts that armor stability should be a function of 10 dimensionless pi terms. One possible set of pi terms is

$$\pi_1 = \frac{\gamma_a^{1/3} H}{\left( \frac{\gamma_a}{\gamma_w} - 1 \right) W_a^{1/3}} \quad (1)$$

$$\pi_2 = H/d \quad (2)$$

$$\pi_3 = H/L \quad (3)$$

$$\pi_4 = \frac{\gamma_a}{\gamma_w} \quad (4)$$

$$\pi_5 = \cot \alpha \quad (5)$$

$$\pi_6 = \Delta \quad (6)$$

$$\pi_7 = \theta \quad (7)$$

$$\pi_8 = \frac{(gH)^{1/2} w_a^{1/3}}{\nu \gamma_a^{1/3}} \quad (8)$$

$$\pi_9 = PT \quad (9)$$

$$\pi_{10} = D \quad (10)$$

Correlation of the test data will be attempted by the functional relationship

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}) \quad (11)$$

or

$$\frac{\gamma_a^{1/3} H}{\left(\frac{\gamma_a}{\gamma_w} - 1\right) w_a^{1/3}} = f \left[ H/d, H/L, \frac{\gamma_a}{\gamma_w}, \cot \alpha, \Delta, \theta, \frac{(gH)^{1/2} w_a^{1/3}}{\nu \gamma_a^{1/3}}, PT, D \right] \quad (12)$$

### Wave Runup

10. Before a breakwater design can be optimized, it is necessary for the designer to be able to accurately estimate wave runup ( $R_u$ ) for the anticipated range of wave conditions to which the structure will be subjected.

Runup data are necessary for selecting a crown elevation that will prevent excessive wave overtopping.

11. The primary variables affecting wave runup on sloping structures are  $\alpha$ ,  $\theta$ ,  $\Delta$ ,  $H$ ,  $d$ ,  $L$ ,  $\beta$  and the porosity ( $P$ ) of the armor layer and underlayers, i.e.,

$$R_u = f(\alpha, \Delta, H, d, L, P, \beta, \theta) \quad (13)$$

One possible set of pi terms is

$$\pi_1 = R_u/H \quad (14)$$

$$\pi_2 = \Delta \quad (15)$$

$$\pi_3 = H/L \quad (16)$$

$$\pi_4 = H/d \quad (17)$$

$$\pi_5 = \alpha \quad (18)$$

$$\pi_6 = P \quad (19)$$

$$\pi_7 = \frac{\beta}{\theta} \quad (20)$$

Correlation of the test data will be attempted by the functional relationship

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7) \quad (21)$$

or

$$R_u/H = f\left(\Delta, H/L, H/d, \alpha, P, \frac{\beta}{\theta}\right) \quad (22)$$

#### Stability Scale Effects

12. If the absolute sizes of experimental breakwater materials and wave dimensions become too small, flow around the armor units enters the laminar regime; and the induced drag forces become a direct function of the Reynolds number. Under these circumstances, prototype phenomena are not properly simulated and stability scale effects are induced. Hudson (1975) presents a

detailed discussion of the design requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater tests and concludes that scale effects will be negligible if the Reynolds stability number,  $R_N = (g^{1/2} H^{1/2} \ell_a) / \nu$ , is equal to or greater than  $3 \times 10^4$ . For all tests reported herein, the sizes of experimental armor and wave dimensions were selected such that scale effects were insignificant (i.e.,  $R_N$  was greater than  $3 \times 10^4$ ).

## PART III: TESTS

### Selection of Test Conditions

13. A review of past site-specific stability projects and hydrographic data showed that typical prototype sea-bottom slopes could range from almost flat to as steep as 1V on 10H. Realizing that wave deformation and severity of breaking action increases as bottom slope increases and since time restraints would allow testing of only one foreslope, it was decided to use a 1V-on-10H slope, thus ensuring severe depth-limited breaking wave action (plunging breakers). This type of breaking wave normally causes the most damage to rubble-mound structures.

14. By nondimensionalizing design conditions from site-specific projects, it was found that a  $d/L$  range of 0.04 to 0.14 should include most prototype conditions encountered in breaking-wave stability designs. A review of capabilities of the available flume and wave generator showed that this range of  $d/L$  values could be achieved for a reasonable range of testing depths.

15. In planning a stability investigation, it is not possible to pre-select exact values of  $H/L$  and  $H/d$  since the design-wave heights are unknown at the outset of the study. However, the widest possible range of these parameters can be ensured by using various armor weights that range from just above the scale-effect regime at the lower limit up to the maximum weights that the test facility is capable of displacing. For the present investigation, armor weights ranged from 0.23 to 0.71 lb.\*

16. The wave flume was calibrated for depths from 0.40 to 0.95 ft in 0.05-ft increments at  $d/L$  values of 0.04, 0.06, 0.08, 0.10, 0.12, and 0.14. This range of depths and consequently breaking wave heights proved to be compatible with the selected armor weights and sea-side breakwater slopes.

17. All stability and wave runup tests were conducted on sections of the type shown in Plate 1 and Photos 1-16. Sea-side slopes of 1V on 1.5H, 1V on 2H, and 1V on 3H were investigated while the beach-side slope was held constant at 1V on 1.5H. Structure heights varied from 1.0 to 1.6 ft. The height

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\* A table of factors for converting U. S. customary units of measurements to metric (SI) units is presented on page 3.

necessary to prevent wave overtopping was determined by the combination of slope, armor type and weight, and water depth being investigated.

### Test Procedures

#### Method of constructing test sections

18. All experimental breakwater sections were constructed to reproduce as closely as possible results of the usual methods of constructing full-scale breakwaters. The core material was dampened as it was dumped by bucket or shovel into the flume and was compacted with hand trowels to simulate natural consolidation resulting from wave action during construction of the prototype structure. Once the core material was in place, it was sprayed with a low-velocity water hose to ensure adequate compaction of the material. The underlayer stone was then added by shovel and smoothed to grade by hand or with trowels. No excessive pressure or compaction was applied during placement of the underlayer stone. Armor units used in the cover layers were placed in a random manner corresponding to work performed by a general coastal contractor, i.e., they were individually placed but were laid down without special orientation or fitting. After each test the armor units were removed from the breakwater, all of the underlayer stones were replaced to the grade of the original test section, and the armor was replaced.

#### Selection of critically breaking waves

19. For a given wave period and water depth, the most detrimental breaking wave (i.e., the most damaging wave) was determined by increasing the stroke adjustment on the wave generator in small increments and observing which wave produced the most severe breaking wave condition on the experimental structures. Wave heights of lower amplitude did not form the critical breaking wave and wave heights of larger amplitude would break seaward of the test structures and dissipate their energy so that they were less damaging than the critically tuned wave.

20. A typical stability test consisted of subjecting the test section to attack by waves of a given height and period until it was certain no damage was going to occur or if damage was occurring, until all damage had abated or the amount of damage exceeded an acceptable level. Test sections were

subjected to wave attack in approximately 30-sec intervals between which the wave generator was stopped and the waves were allowed to decay to zero height. This procedure was necessary to prevent the structures from being subjected to an undefined wave system created by reflections from the experimental breakwater and wave generator. Newly built test sections were subjected to a short duration (five or six 30-sec intervals) of shakedown using a wave equal in height to about one-half of the estimated no-damage wave. This procedure provided a means of allowing consolidation and armor unit seating that would normally occur during prototype construction.

#### Method of determining damage

21. In order to evaluate and compare breakwater stability test results, it is necessary to quantify the changes that have taken place in a given structure during attack by waves of specified characteristics. The U. S. Army Engineer Waterways Experiment Station (WES) developed a method of measuring the percent damage incurred by a test section during the early 1950's. This method has proven satisfactory and was used as a means for analyzing and comparing the stability tests delineated herein.

22. The WES damage-measurement technique requires that the cross-sectional area occupied by armor units be determined for each stability test section. Armor unit area is computed from elevations (soundings) taken at closely spaced grid-point locations over the seaward face of the structure before the armor is placed on the underlayer, after the armor has been placed but before the section has been subjected to wave attack, and finally after wave attack. Elevations are obtained with a sounding rod equipped with a circular spirit level for plumbing, a scale graduated in thousandths of a foot, and a ball-and-socket foot for adjustment to the irregular surface of the breakwater slope. The diameter (Diam) in inches of the circular foot of the sounding rod was related to the size of the material being sounded by the following equation:

$$\text{Diam} = C \left( \frac{W_a}{Y_a} \right)^{1/3} \quad (23)$$

where  $C = 6.8$  and  $13.7$  for stone and dolosse, respectively. A series of sounding tests in which both the weight of the armor and the diameter of the sounding foot were varied indicated that the above relation would give a

measured thickness which visually appeared to represent an acceptable two-layer thickness.

23. Sounding data for each test section were obtained as follows: after the underlayer was in place, soundings were taken on the sea-side slope of the structure along rows beginning at and parallel to the longitudinal center line of the structure and extending in 0.25-ft horizontal increments until the interface between the structure's toe and the flume bottom was reached. On each parallel row, 13 sounding points, spaced at 0.25-ft increments, were measured. This distance represented the middle 3 ft of a 5-ft-wide test section; the 1 ft of structure next to each wall was not considered because of the possibility of discontinuity effects between the armor units and the flume walls. Soundings were taken at the same points once the armor was in place and again after the structure had been subjected to wave attack.

24. Sounding data from each stability test were reduced in the following manner. The individual sounding points obtained on each parallel row were averaged to yield an average elevation at the bottom of the armor layer before the armor was placed and then at the top of the armor layer before and after testing. From these values, the cross-sectional armor area before testing and the area from which armor units were displaced (either downslope or off the section) were calculated. Damage was then determined from the following relation:

$$\text{Percent damage} = \frac{A_2}{A_1} (100) \quad (24)$$

where

$A_1$  = area before testing,  $\text{ft}^2$

$A_2$  = area from which armor units have been displaced,  $\text{ft}^2$

The percentage given by the WES sounding technique is, therefore, a measurement of an end area which converts to an average volume of armor material that has been moved from its original location (either downslope or off-structure).

#### Measurement of wave runup

25. Values of wave runup were obtained with a point gage calibrated in increments of 0.001 ft and mounted on an aluminum framework that could be moved along and across the seaward breakwater slope. Due to slight height variations from wave to wave within a given wave train and the highly porous

texture of the breakwater slope, five measurements of  $R_u$  were made for each test wave condition. Photos 17-22 show breaking and runup for selected wave conditions. Runup values were taken as the upper edge of the solid water, not the foam or splash line.

### Test Equipment and Materials

#### Equipment used

26. All wave-action tests were conducted in a 5-ft-wide, 4-ft-deep, and 119-ft-long concrete wave flume with test sections installed about 90 ft from a vertical displacement wave generator. The first 10 ft of flume bottom, immediately seaward of the test sections, was molded on a 1V-on-10H slope while the remaining 80 ft was flat. The generator is capable of producing sinusoidal waves of various periods and heights. Test waves of the required characteristics were generated by varying the frequency and amplitude of the plunger motion. Changes in water-surface elevation as a function of time (wave heights) were measured by electrical wave-height gages in the vicinity of where the toe of the test sections was to be placed and recorded on chart paper by an electrically operated oscillograph. The electrical output of the wave gages was directly proportional to their submergence depth.

#### Materials used

27. Rough hand-shaped granitic stone ( $W_a$ ) with an average length of approximately two times its width, average weights of 0.38 lb ( $\pm 0.02$  lb), 0.55 lb ( $\pm 0.025$  lb), and 0.71 lb ( $\pm 0.03$  lb), and a specific weight of 167 pcf was used to armor the stone sections. Dolos sections were armored with the following sizes of units.

$W_a$ , lb	$\gamma_a$ , pcf
0.234	137.7
0.276	142.2
0.589	141.1

Sieve-sized limestone ( $\gamma_a = 165.0$  pcf) was used for the underlayer ( $W_1$ ) and core ( $W_2$ ).

## PART IV: TEST RESULTS

### Stability Tests

28. Breaking wave stability test results for stone and dolos armor are summarized in Tables 1 and 2, respectively. Presented therein are experimentally determined design wave heights and corresponding stability numbers as functions of relative depth, wave steepness, relative wave height, Ursell Number ( $N_u$ ), and breakwater slope. All stability test results presented in Tables 1 and 2 were verified by at least one repeat test. Sea-side breakwater slopes of 1V on 1.5H, 1V on 2H, 1V on 3H were used for both armor types. The following ranges of armor weights, water depths, wave periods and heights, relative depths, wave steepness, Ursell Numbers, and relative wave heights were investigated.

Variable	Range for Indicated Type of Armor	
	Stone	Dolosse
Armor weight, lb	0.38-0.71	0.234-0.589
Water depth, ft	0.40-0.75	0.45-0.95
Wave period, sec	1.04-2.82	1.30-2.32
Wave height, ft	0.33-0.55	0.45-0.77
Relative depth	0.04-0.14	0.06-0.14
Wave steepness	0.042-0.099	0.058-0.094
Relative wave height	0.64-1.05	0.64-1.02
Ursell Number	32.5-656.3	33.6-284.0

The number of armor units per given surface area,  $A$ , was  $N = 1.26 \Psi^{-2/3}$ , with  $n = 2$ ,  $k_\Delta = 1.00$ , and  $P = 37$  percent for stone armor, and  $N = 0.83 \Psi^{-2/3}$  with  $n = 2$ ,  $k_\Delta = 0.94$ , and  $P = 56$  percent for dolos armor. The variable,  $\Psi$ , is defined as the volume of an individual armor unit. It should be noted that  $k_\Delta = 1.00$  obtained from numerous stone armor tests is less than the present SPM (CERC 1977) value of 1.15. Photos 23-63 show the after-testing stability condition of the structures.

29. As previously discussed, it was hoped that stability test results could be analyzed by the following functional relation for the stability number,  $N_s$ , where

$$N_s = \frac{\gamma_a^{1/3} H}{(S_a - 1) W_a^{1/3}} = f \left[ H/d, H/L, \frac{\gamma_a}{\gamma_w}, \cot \alpha, \theta, \Delta, (gH)^{1/2} \ell_a / \nu, PT, D \right] \quad (25)$$

For tests described herein  $\theta$ ,  $PT$ , and  $D$  were held constant and  $\gamma_a/\gamma_w$  was essentially invariant for a given type of armor; therefore Equation 25 reduces to

$$N_s = f \left[ H/d, H/L, \cot \alpha, \Delta, (gH)^{1/2} \ell_a / \nu \right] \quad (26)$$

Also, the sizes of experimental armor units and wave dimensions were selected such that turbulent flow was always obtained; therefore  $N_s$  was independent of Reynolds number  $\left[ (gH)^{1/2} \ell_a / \nu \right]$  and Equation 26 becomes

$$N_s = f(H/d, H/L, \cot \alpha, \Delta) \quad (27)$$

30. Plots of  $N_s$  versus  $H/d$  and  $H/L$  are presented in Plates 2 and 3, respectively. Effects of  $H/d$  and  $H/L$  are combined in the Ursell Number ( $L^2 H/d^3$ ) and results are given in Plate 4. These data show a weak functional dependence of  $N_s$  on  $H/d$ ,  $H/L$ , and  $L^2 H/d^3$  with the dependence being more pronounced for dolos armor. For both armor types, it generally appears that minimum stability occurs for the larger values of  $H/d$  and  $L^2 H/d^3$  and for the intermediate range of  $H/L$  ( $0.07 \leq H/L \leq 0.085$ ). Results of previous tests conducted on quarystone by Hudson (1958) and Carver (1980) for nonbreaking waves,  $H/d \leq 0.32$  and  $0.03 \leq H/L \leq 0.08$ , do not show these trends. Also the trends are absent from earlier nonbreaking wave tests on dolosse (Carver and Davidson 1977). The tests of Carver and Davidson were conducted with  $H/d \leq 0.37$  and  $0.031 \leq H/L \leq 0.083$ .

31. Plate 5 presents a log-log plot of  $N_s$  versus  $\cot \alpha$ . Average and lower limit linear fits of the Hudson type, i.e., 1V-on-3H slope linear fits, are also shown. Even though there is some data spread for each distinct value of  $\cot \alpha$  (due to variations of  $H/d$ ,  $H/L$ , and  $L^2 H/d^3$ ), the linear fits generally give a reasonable approximation of  $N_s$  as a function of  $\cot \alpha$ , especially for stone armor. The lower limit lines correspond to stability coefficient ( $K_D$ ) values of 2.0 and 15.0 for stone and dolosse, respectively.

### Wave Runup Tests

32. Runup, average runup, and the standard deviation are shown in Tables 3 and 4 for all test conditions. Considering the small random variations inherent in test waves within a given wave train and small local variations in the texture and porosity of the breakwater slope, test results appear to be quite consistent.

33. As described in paragraph 11, it was hoped that runup test results could be correlated by the following functional relation for relative runup ( $R_u/H$ )

$$R_u/H = f\left(\Delta, H/L, H/d, \alpha, P, \frac{\beta}{\theta}\right) \quad (22 \text{ bis})$$

For runup tests described herein  $P$  was constant for a given type of armor and  $\beta/\theta$  was invariant for all tests; therefore Equation 22 reduces to

$$R_u/H = f(\Delta, H/L, H/d, \alpha) \quad (28)$$

Calculated values of relative runup along with corresponding values of  $H/L$ ,  $H/d$ , and  $\cot \alpha$  are presented in Tables 5 and 6 using the average runup from Tables 3 and 4. Plates 6-11 present  $R_u/H$  as a function of  $H/L$  for constant values of  $\cot \alpha$  and Plates 12-17 present  $R_u/H$  as a function of  $H/d$  for constant values of  $\cot \alpha$ . These data show relative runup to be a function of breakwater slope, wave steepness, relative wave height, and armor type. It is very interesting to note that maximum values of  $R_u/H$  are generally observed in the same  $H/L$  and  $H/d$  ranges that minimum stability was obtained, i.e.,  $N_s$  is a minimum and  $R_u/H$  is a maximum when  $H/d \geq 0.90$  and  $0.06 \leq H/L \leq 0.085$ . Consistent with nonbreaking wave data (Hudson 1958, Jackson 1968, Carver and Davidson 1977, Carver 1980) flattening the slope from 1V on 1.5H to 1V on 3H generally reduced runup. The general tendency for runup to decrease at the milder slopes seems reasonable since as the slope becomes flatter the wave has a longer travel distance to reach a given elevation and, therefore, a greater opportunity to dissipate energy.

34. Hudson (1958) found that for nonbreaking wave attack on stone armor, plots of  $R_u/H$  versus  $H/L$  gave concave curves; i.e., for small values of  $H/L$ ,  $R_u/H$  is relatively large and as  $H/L$  increases  $R_u/H$

increases to a maximum value and then decreases as  $H/L$  continues to increase. Data presented in Plates 6-8 show a trend very similar to that observed by Hudson and the dolos trends evident in Plates 9-11 are similar to those observed by Carver and Davidson (1977). Recent runup tests on stone armor by Carver (1980) show a similar dependency between  $R_u/H$  and  $H/L$  to that observed in the data presented herein. Maximum observed values of  $R_u/H$  reported herein are generally 10 to 20 percent less than those obtained by Hudson (1958), Carver and Davidson (1977), and Carver (1980) in nonbreaking wave tests. This trend seems consistent since (for breaking waves) energy is dissipated in the turbulence of breaking; therefore less energy is available to produce runup. It should be noted that for very steep structure slopes, such as those found in bulkheads and seawalls, breaking wave runup may be greater than nonbreaking wave runup. This occurs when plunging breakers impact directly on a near-vertical wall and the force of breaking causes a shooting type of runup on the wall. The dependency of  $R_u/H$  on  $H/d$ , evident in the present investigation, was not observed in the earlier nonbreaking wave tests for the following reasons: (a) all nonbreaking wave tests were conducted in an  $H/d$  range of 0.1 to 0.3; therefore  $H/d$  was sufficiently low to preclude a significant effect on wave form, and (b) the range of  $H/d$  was too limited ( $0.1 \leq H/d \leq 0.3$ ) for a subtle trend (even if one were present) to be detected.

## PART V: CONCLUSIONS AND RECOMMENDATIONS

35. Based on the tests and results described herein, in which stone and dolos armor are used on breakwater trunks and subjected to breaking waves with a direction of approach of 90 deg, it is concluded that:

- a. Armor stability is influenced by wave steepness ( $H/L$ ), Ursell Number ( $L^2H/d^3$ ), relative wave height ( $H/d$ ), and breakwater slope.
- b. Effects of  $H/d$ ,  $L^2H/d^3$ , and  $H/L$  are more pronounced for dolos armor.
- c. In general, minimum stability for each armor type occurred for the larger values of  $H/d$  ( $H/d > 0.90$ ), intermediate values of  $H/L$  ( $0.06 \leq H/L \leq 0.085$ ), and larger values of  $L^2H/d^3$ .
- d. Linear Hudson-type data fits generally give a reasonable approximation of  $N_s$  as a function of  $\cot \alpha$ ; however, the influences of  $H/d$ ,  $H/L$ , and  $L^2H/d^3$  are strong enough to merit their consideration in final selection of armor unit weight.
- e. Relative wave runup ( $R_u/H$ ) is a function of wave steepness ( $H/L$ ), relative wave height ( $H/d$ ), type of armor, and breakwater slope.
- f. Maximum values of  $R_u/H$  were generally observed in the same  $H/L$  and  $H/d$  ranges that minimum stability was obtained.
- g. Lower limit  $K_D$  values (i.e., values that will yield a stable design for any combination of wave height, wave period, and water depth investigated herein) obtained in this study are 2.0 and 15.0 for stone and dolosse, respectively.

36. Based on the above conclusions, it is recommended that armor stability for breaking waves be presented as a function of wave height, wave period, and water depth (e.g., Ursell Number). If wave conditions vary significantly or their precise combinations cannot be accurately defined, then the lower limit  $K_D$  coefficients given in item g above should be used. It should be noted that the  $K_D$  values of 2.0 and 15.0 (lower limits of the stone and dolos data presented herein) are significantly different from those presented in the SPM (CERC 1977) and EM 1110-2-2904 (USAOCE 1963).

37. It is presumed that conclusions reached as a result of these tests can be extended to wave spectra, most probably using the period and energy density associated with the spectral peak (especially for relatively narrow spectra). Future testing programs are planned to address the more complex questions of bimodal and directional spectra.

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Table 1

Values of  $H_{D=0}$ ,  $d/L$ ,  $H/L$ ,  $H/d$ ,  $L^2H/d^3$ , and  $N_s$  for Two Layers of Stone Armor Randomly Placed on Breakwater Trunks and Subjected to Breaking Waves with No Overtopping:  $W_a = 0.38, 0.55$ , and  $0.71$  lb;  $\gamma_a = 167$  pcf;  $\cot \alpha = 1.5, 2$ , and  $3$

$W_a$ , lb	$d$ , ft	$T$ , sec	$H_{D=0}$ , ft	$d/L$	$H/L$	$H/d$	$L^2H/d^3$	$N_s$
<u><math>\cot \alpha = 1.5</math></u>								
0.38	0.45	1.07	0.33	0.12	0.088	0.73	50.9	1.50
0.38	0.55	1.04	0.35	0.14	0.089	0.64	32.5	1.59
0.55	0.40	1.45	0.37	0.08	0.074	0.93	144.5	1.48
0.55	0.55	1.18	0.38	0.12	0.083	0.69	48.0	1.52
0.55	0.60	1.09	0.40	0.14	0.093	0.67	34.0	1.60
0.71	0.40	1.90	0.42	0.06	0.063	1.05	291.7	1.55
0.71	0.40	2.82	0.42	0.04	0.042	1.05	656.3	1.55
0.71	0.50	1.32	0.42	0.10	0.084	0.84	84.0	1.55
<u><math>\cot \alpha = 2.0</math></u>								
0.38	0.50	1.13	0.41	0.12	0.098	0.82	56.9	1.86
0.38	0.55	1.18	0.38	0.12	0.083	0.69	48.0	1.72
0.38	0.60	1.09	0.40	0.14	0.093	0.67	34.0	1.81
0.55	0.40	2.82	0.42	0.04	0.042	1.05	656.3	1.68
0.55	0.50	1.32	0.42	0.10	0.084	0.84	84.0	1.68
0.55	0.60	1.24	0.45	0.12	0.090	0.75	52.1	1.80
0.55	0.65	1.13	0.46	0.14	0.099	0.71	36.1	1.84
0.71	0.45	2.02	0.46	0.06	0.061	1.02	284.0	1.69
0.71	0.65	1.29	0.51	0.12	0.094	0.78	54.5	1.88
<u><math>\cot \alpha = 3.0</math></u>								
0.38	0.40	2.82	0.42	0.04	0.042	1.05	656.3	1.90
0.38	0.60	1.24	0.45	0.12	0.090	0.75	52.1	2.04
0.38	0.65	1.13	0.46	0.14	0.099	0.71	36.1	2.09
0.55	0.45	2.02	0.46	0.06	0.061	1.02	284.0	1.84
0.55	0.60	1.45	0.52	0.10	0.087	0.87	86.7	2.09
0.55	0.65	1.29	0.51	0.12	0.094	0.78	54.5	2.04
0.55	0.75	1.38	0.55	0.12	0.088	0.73	50.9	2.21

Table 2

Values of  $H_{D=0}$ ,  $d/L$ ,  $H/L$ ,  $H/d$ ,  $L^2H/d^3$ , and  $N_s$  for Two Layers of Dolos Armor Randomly Placed on Breakwater Trunks and Subjected to Breaking Waves with No Overtopping:  $W_a = 0.234, 0.276$ , and  $0.589$  lb;  $\cot \alpha = 1.5, 2$ , and  $3$

$W_a$ , lb	$d$ , ft	$T$ , sec	$H_{D=0}$ , ft	$d/L$	$H/L$	$H/d$	$L^2H/d^3$	$N_s$
<u><math>\cot \alpha = 1.5</math></u>								
0.276	0.45	2.02	0.46	0.06	0.061	1.02	284.0	2.88
0.276	0.50	1.62	0.45	0.08	0.072	0.90	140.6	2.82
0.589	0.65	1.85	0.60	0.08	0.074	0.92	144.2	2.95
0.589	0.85	1.73	0.71	0.10	0.084	0.84	83.5	3.50
0.589	0.90	1.78	0.77	0.10	0.086	0.86	85.6	3.79
<u><math>\cot \alpha = 2.0</math></u>								
0.234	0.45	2.02	0.46	0.06	0.061	1.02	284.0	3.19
0.276	0.55	1.70	0.54	0.08	0.079	0.98	153.4	3.39
0.276	0.85	1.30	0.56	0.14	0.092	0.66	33.6	3.51
0.276	0.85	1.47	0.63	0.12	0.089	0.74	51.5	3.95
0.276	0.95	1.37	0.61	0.14	0.090	0.64	32.8	3.82
<u><math>\cot \alpha = 3.0</math></u>								
0.234	0.70	1.34	0.55	0.12	0.094	0.79	54.6	3.82
0.234	0.80	1.43	0.55	0.12	0.083	0.69	47.7	3.82
0.234	0.85	1.30	0.56	0.14	0.092	0.66	33.6	3.89
0.276	0.60	2.32	0.58	0.06	0.058	0.97	268.5	3.64
0.276	0.65	1.85	0.60	0.08	0.074	0.92	144.2	3.76
0.276	0.90	1.52	0.64	0.12	0.085	0.71	49.4	4.01
0.276	0.95	1.56	0.66	0.12	0.083	0.69	48.2	4.14

Table 3  
Wave Runup ( $R_u$ ) Data for Quarystone Armor Randomly Placed  
on Breakwater Trunks and Subjected to Breaking Waves with  
No Overtopping:  $\cot \alpha = 1.5, 2.0, \text{ and } 3.0$

d, ft	T, sec	H, ft	$R_u$ , ft, for Test					Average	Standard Deviation, ft	
			1	2	3	4	5			
<u><math>\cot \alpha = 1.5</math></u>										
0.40	0.89	0.27	0.21	0.23	0.22	0.22	0.24	0.22	0.012	
0.40	1.01	0.33	0.31	0.27	0.29	0.30	0.29	0.29	0.015	
0.40	1.18	0.36	0.34	0.36	0.35	0.33	0.37	0.35	0.016	
0.40	1.45	0.37	0.37	0.40	0.40	0.42	0.40	0.40	0.018	
0.40	1.90	0.42	0.50	0.45	0.44	0.48	0.42	0.46	0.032	
0.40	2.82	0.42	0.40	0.38	0.38	0.42	0.40	0.40	0.017	
0.45	0.94	0.31	0.31	0.26	0.22	0.28	0.25	0.26	0.034	
0.45	1.07	0.33	0.32	0.32	0.34	0.30	0.35	0.33	0.020	
0.45	1.26	0.39	0.33	0.36	0.36	0.37	0.35	0.35	0.016	
0.50	0.99	0.30	0.32	0.30	0.30	0.28	0.30	0.30	0.014	
0.50	1.13	0.41	0.38	0.38	0.36	0.35	0.38	0.37	0.014	
0.50	1.32	0.42	0.38	0.38	0.42	0.42	0.38	0.40	0.022	
0.55	1.04	0.35	0.32	0.33	0.31	0.35	0.33	0.33	0.015	
0.55	1.18	0.38	0.42	0.42	0.42	0.38	0.42	0.41	0.018	
0.60	1.09	0.40	0.38	0.41	0.41	0.37	0.39	0.39	0.018	
<u><math>\cot \alpha = 2.0</math></u>										
0.40	0.89	0.27	0.21	0.18	0.17	0.20	0.17	0.19	0.019	
0.40	1.01	0.33	0.20	0.19	0.18	0.22	0.19	0.20	0.016	
0.40	1.18	0.36	0.23	0.24	0.23	0.26	0.24	0.24	0.012	
0.40	1.45	0.37	0.28	0.28	0.32	0.28	0.29	0.29	0.017	
0.40	1.90	0.42	0.36	0.29	0.34	0.36	0.39	0.35	0.037	
0.40	2.82	0.42	0.28	0.32	0.29	0.30	0.31	0.30	0.016	
0.45	0.94	0.31	0.17	0.17	0.18	0.16	0.17	0.17	0.007	
0.45	1.07	0.33	0.21	0.23	0.23	0.25	0.19	0.22	0.023	
0.45	1.26	0.39	0.28	0.26	0.28	0.30	0.29	0.28	0.015	
0.45	1.54	0.44	0.36	0.35	0.37	0.33	0.34	0.35	0.016	
0.45	2.02	0.46	0.32	0.34	0.39	0.37	0.40	0.36	0.034	
0.50	0.99	0.30	0.15	0.18	0.20	0.21	0.18	0.18	0.023	
0.50	1.13	0.41	0.29	0.23	0.23	0.22	0.23	0.24	0.028	
0.50	1.32	0.42	0.26	0.27	0.27	0.28	0.27	0.27	0.007	
0.50	1.62	0.45	0.38	0.37	0.39	0.39	0.38	0.38	0.009	
0.55	1.04	0.35	0.22	0.20	0.22	0.24	0.23	0.22	0.015	
0.55	1.18	0.38	0.23	0.27	0.26	0.27	0.26	0.26	0.017	
0.55	1.39	0.45	0.34	0.35	0.32	0.29	0.35	0.33	0.025	

(Continued)

Table 3 (Concluded)

d, ft	T, sec	H, ft	R <sub>u</sub> , ft, for Test					Average	Standard Deviation, ft	
			1	2	3	4	5			
<u>cot α = 2.0 (Continued)</u>										
0.60	1.09	0.40	0.25	0.28	0.26	0.29	0.28	0.27	0.017	
0.60	1.24	0.45	0.27	0.36	0.28	0.30	0.30	0.30	0.035	
0.65	1.13	0.46	0.28	0.31	0.34	0.31	0.28	0.30	0.025	
0.65	1.29	0.51	0.33	0.38	0.33	0.33	0.34	0.34	0.022	
0.70	1.18	0.46	0.31	0.32	0.33	0.32	0.35	0.33	0.016	
<u>cot α = 3.0</u>										
0.40	0.89	0.27	0.14	0.11	0.14	0.14	0.11	0.13	0.017	
0.40	1.01	0.33	0.18	0.19	0.18	0.18	0.19	0.18	0.007	
0.40	1.18	0.36	0.20	0.22	0.21	0.22	0.22	0.21	0.010	
0.40	1.45	0.37	0.23	0.22	0.24	0.23	0.21	0.23	0.012	
0.40	1.90	0.42	0.31	0.24	0.30	0.28	0.25	0.28	0.031	
0.40	2.82	0.42	0.29	0.27	0.28	0.28	0.29	0.28	0.009	
0.45	0.94	0.31	0.14	0.16	0.14	0.16	0.16	0.15	0.011	
0.45	1.07	0.33	0.19	0.19	0.18	0.17	0.17	0.18	0.010	
0.45	1.26	0.39	0.23	0.25	0.22	0.18	0.19	0.21	0.029	
0.45	1.54	0.44	0.26	0.27	0.27	0.26	0.24	0.26	0.012	
0.45	2.02	0.46	0.32	0.32	0.35	0.33	0.33	0.33	0.012	
0.50	0.99	0.30	0.15	0.17	0.15	0.15	0.16	0.16	0.010	
0.50	1.13	0.41	0.21	0.19	0.21	0.20	0.20	0.20	0.009	
0.50	1.32	0.42	0.21	0.23	0.21	0.25	0.23	0.23	0.017	
0.50	1.62	0.45	0.28	0.28	0.27	0.25	0.29	0.27	0.016	
0.55	1.04	0.35	0.19	0.18	0.15	0.20	0.17	0.18	0.019	
0.55	1.18	0.38	0.19	0.26	0.19	0.25	0.22	0.22	0.033	
0.55	1.39	0.45	0.30	0.31	0.34	0.30	0.31	0.31	0.017	
0.55	1.70	0.54	0.38	0.37	0.38	0.39	0.37	0.38	0.009	
0.60	1.09	0.40	0.24	0.23	0.22	0.23	0.20	0.22	0.016	
0.60	1.24	0.45	0.22	0.25	0.27	0.29	0.26	0.26	0.026	
0.60	1.45	0.52	0.34	0.35	0.33	0.34	0.33	0.34	0.009	
0.65	1.13	0.46	0.26	0.26	0.24	0.26	0.26	0.26	0.010	
0.65	1.29	0.51	0.29	0.30	0.28	0.31	0.30	0.30	0.012	
0.70	1.18	0.46	0.30	0.31	0.27	0.31	0.31	0.30	0.017	
0.70	1.34	0.55	0.36	0.35	0.37	0.38	0.35	0.36	0.013	
0.75	1.22	0.44	0.28	0.26	0.27	0.28	0.28	0.27	0.010	
0.75	1.38	0.55	0.35	0.33	0.36	0.37	0.34	0.35	0.016	

Table 4  
Wave Runup ( $R_u$ ) Data for Dolos Armor Randomly Placed on  
Breakwater Trunks and Subjected to Breaking Waves  
with No Overtopping:  $\cot \alpha = 1.5, 2.0, \text{ and } 3.0$

d, ft	T, sec	H, ft	R <sub>u</sub> , ft, for Test					Average	Standard Deviation, ft.	
			1	2	3	4	5			
<u>cot α = 1.5</u>										
0.40	1.45	0.37	0.25	0.24	0.26	0.22	0.26	0.25	0.017	
0.40	1.90	0.42	0.32	0.32	0.32	0.32	0.32	0.32	0.000	
0.40	2.82	0.42	0.30	0.30	0.27	0.30	0.31	0.30	0.016	
0.45	0.94	0.31	0.19	0.18	0.16	0.16	0.19	0.18	0.016	
0.45	1.26	0.39	0.27	0.27	0.24	0.28	0.27	0.27	0.016	
0.45	1.54	0.44	0.33	0.34	0.34	0.32	0.35	0.34	0.012	
0.45	2.02	0.46	0.35	0.35	0.35	0.35	0.35	0.35	0.000	
0.50	0.99	0.30	0.20	0.20	0.17	0.21	0.22	0.20	0.019	
0.50	1.32	0.42	0.28	0.26	0.27	0.28	0.30	0.28	0.015	
0.50	1.62	0.45	0.38	0.35	0.37	0.38	0.39	0.37	0.016	
0.55	1.04	0.35	0.23	0.23	0.23	0.24	0.24	0.23	0.007	
0.55	1.18	0.38	0.30	0.26	0.28	0.28	0.27	0.28	0.015	
0.55	1.70	0.54	0.44	0.44	0.43	0.37	0.40	0.42	0.031	
0.60	1.09	0.40	0.32	0.28	0.27	0.28	0.26	0.28	0.023	
0.65	1.13	0.46	0.32	0.34	0.30	0.31	0.30	0.31	0.017	
0.65	1.29	0.51	0.41	0.40	0.38	0.38	0.40	0.39	0.014	
0.65	1.85	0.60	0.59	0.58	0.60	0.56	0.57	0.58	0.016	
0.70	1.18	0.46	0.33	0.32	0.33	0.34	0.33	0.33	0.007	
0.75	1.99	0.70	0.66	0.68	0.66	0.62	0.64	0.65	0.023	
0.80	1.67	0.66	0.53	0.55	0.59	0.58	0.56	0.56	0.024	
0.85	1.73	0.71	0.64	0.60	0.62	0.60	0.60	0.61	0.018	
0.90	1.78	0.77	0.58	0.62	0.61	0.60	0.62	0.61	0.017	
<u>cot α = 2.0</u>										
0.40	1.45	0.37	0.26	0.24	0.24	0.23	0.26	0.25	0.014	
0.40	1.90	0.42	0.33	0.31	0.30	0.31	0.30	0.31	0.012	
0.40	2.82	0.42	0.26	0.30	0.27	0.29	0.29	0.28	0.017	
0.45	0.94	0.31	0.17	0.17	0.17	0.17	0.16	0.17	0.005	
0.45	1.26	0.39	0.25	0.26	0.25	0.23	0.23	0.24	0.014	
0.45	1.54	0.44	0.33	0.30	0.31	0.30	0.32	0.31	0.013	
0.45	2.02	0.46	0.36	0.37	0.35	0.35	0.34	0.35	0.012	
0.50	0.99	0.30	0.21	0.18	0.20	0.18	0.20	0.19	0.014	
0.50	1.32	0.42	0.27	0.27	0.26	0.25	0.23	0.26	0.017	
0.50	1.62	0.45	0.34	0.37	0.34	0.37	0.33	0.35	0.019	

(Continued)

Table 4 (Concluded)

d, ft	T, sec	H, ft	R <sub>u</sub> , ft, for Test					Average	Standard Deviation, ft
			1	2	3	4	5		
<u>cot α = 2.0 (Continued)</u>									
0.55	1.04	0.35	0.23	0.24	0.22	0.22	0.23	0.23	0.009
0.55	1.18	0.38	0.25	0.26	0.27	0.26	0.27	0.26	0.009
0.55	1.70	0.54	0.36	0.39	0.38	0.39	0.36	0.38	0.016
0.60	1.09	0.40	0.25	0.27	0.25	0.23	0.27	0.25	0.017
0.65	1.13	0.46	0.25	0.24	0.24	0.25	0.25	0.25	0.007
0.65	1.29	0.51	0.31	0.31	0.33	0.33	0.33	0.32	0.011
0.70	1.18	0.46	0.27	0.30	0.32	0.29	0.27	0.29	0.021
0.80	1.43	0.55	0.40	0.41	0.43	0.42	0.45	0.42	0.019
0.85	1.30	0.56	0.43	0.40	0.37	0.38	0.40	0.40	0.023
0.85	1.47	0.44	0.47	0.47	0.48	0.45	0.45	0.46	0.017
0.95	1.37	0.61	0.42	0.42	0.41	0.42	0.40	0.41	0.010
0.95	1.56	0.66	0.50	0.51	0.50	0.50	0.51	0.50	0.007
<u>cot α = 3.0</u>									
0.40	1.45	0.37	0.18	0.20	0.19	0.22	0.20	0.20	0.015
0.40	1.90	0.42	0.29	0.28	0.28	0.28	0.28	0.28	0.005
0.40	2.82	0.42	0.27	0.27	0.25	0.28	0.28	0.27	0.012
0.45	0.94	0.31	0.14	0.15	0.12	0.15	0.15	0.14	0.013
0.45	1.26	0.39	0.22	0.23	0.19	0.20	0.22	0.21	0.017
0.45	1.54	0.44	0.27	0.26	0.25	0.24	0.26	0.26	0.012
0.45	2.02	0.46	0.28	0.28	0.26	0.28	0.28	0.28	0.010
0.50	0.99	0.30	0.18	0.17	0.16	0.17	0.17	0.17	0.007
0.50	1.32	0.42	0.24	0.23	0.23	0.22	0.24	0.23	0.009
0.50	1.62	0.45	0.32	0.30	0.28	0.31	0.30	0.30	0.015
0.55	1.04	0.35	0.20	0.21	0.21	0.20	0.21	0.21	0.007
0.55	1.18	0.38	0.25	0.25	0.23	0.22	0.24	0.24	0.013
0.55	1.70	0.54	0.31	0.32	0.31	0.31	0.32	0.31	0.007
0.60	1.09	0.40	0.22	0.23	0.23	0.22	0.21	0.22	0.009
0.65	1.13	0.46	0.27	0.25	0.24	0.26	0.27	0.26	0.013
0.65	1.29	0.51	0.28	0.30	0.27	0.27	0.28	0.28	0.012
0.65	1.51	0.57	0.30	0.36	0.34	0.36	0.37	0.35	0.028
0.65	1.85	0.60	0.38	0.41	0.40	0.40	0.42	0.40	0.015
0.70	1.18	0.46	0.29	0.27	0.28	0.28	0.26	0.28	0.012
0.70	1.57	0.63	0.34	0.38	0.39	0.37	0.35	0.37	0.021
0.80	1.43	0.55	0.34	0.36	0.34	0.35	0.33	0.34	0.012
0.85	1.30	0.56	0.33	0.34	0.34	0.35	0.33	0.34	0.009
0.85	1.47	0.63	0.38	0.39	0.39	0.37	0.39	0.38	0.010
0.90	1.52	0.64	0.38	0.40	0.40	0.37	0.36	0.38	0.018
0.95	1.37	0.61	0.31	0.35	0.35	0.35	0.33	0.34	0.018
0.95	1.56	0.66	0.35	0.38	0.40	0.40	0.40	0.39	0.022

Table 5  
Values of Relative Runup ( $R_u/H$ ) for Quarystone Armor Randomly  
Placed on Breakwater Trunks and Subjected to Breaking  
Waves with No Overtopping:  $\cot \alpha = 1.5, 2.0, \text{ and } 3.0$

$d, \text{ ft}$	$d/L$	$T, \text{ sec}$	$H, \text{ ft}$	$H/L$	$H/d$	$R_u, \text{ ft}$	$R_u/H$	Standard Deviation, ft
$\cot \alpha = 1.5$								
0.40	0.14	0.89	0.27	0.094	0.68	0.22	0.81	0.04
0.40	0.12	1.01	0.33	0.099	0.83	0.29	0.88	0.05
0.40	0.10	1.18	0.36	0.090	0.90	0.35	0.97	0.04
0.40	0.08	1.45	0.37	0.074	0.93	0.40	1.08	0.05
0.40	0.06	1.90	0.42	0.063	1.05	0.46	1.10	0.08
0.40	0.04	2.82	0.42	0.042	1.05	0.40	0.95	0.04
0.45	0.14	0.94	0.31	0.097	0.69	0.26	0.84	0.11
0.45	0.12	1.07	0.33	0.088	0.73	0.33	1.00	0.06
0.45	0.10	1.26	0.39	0.087	0.87	0.35	0.90	0.04
0.50	0.14	0.99	0.30	0.084	0.60	0.30	1.00	0.05
0.50	0.12	1.13	0.41	0.098	0.82	0.37	0.90	0.03
0.50	0.10	1.32	0.42	0.084	0.84	0.40	0.95	0.05
0.55	0.14	1.04	0.35	0.089	0.64	0.33	0.94	0.04
0.55	0.12	1.18	0.38	0.083	0.69	0.41	1.08	0.05
0.60	0.14	1.09	0.40	0.093	0.67	0.39	0.98	0.05
$\cot \alpha = 2.0$								
0.40	0.14	0.89	0.27	0.094	0.68	0.19	0.70	0.07
0.40	0.12	1.01	0.33	0.099	0.83	0.20	0.61	0.05
0.40	0.10	1.18	0.36	0.090	0.90	0.24	0.67	0.03
0.40	0.08	1.45	0.37	0.074	0.93	0.29	0.78	0.05
0.40	0.06	1.90	0.42	0.063	1.05	0.35	0.83	0.09
0.40	0.04	2.82	0.42	0.042	1.05	0.30	0.71	0.04
0.45	0.14	0.94	0.31	0.097	0.69	0.17	0.55	0.02
0.45	0.12	1.07	0.33	0.088	0.73	0.22	0.67	0.07
0.45	0.10	1.26	0.39	0.087	0.87	0.28	0.72	0.04
0.45	0.08	1.54	0.44	0.078	0.98	0.35	0.80	0.04
0.45	0.06	2.02	0.46	0.061	1.02	0.36	0.78	0.07
0.50	0.14	0.99	0.30	0.084	0.60	0.18	0.60	0.08
0.50	0.12	1.13	0.41	0.098	0.82	0.24	0.59	0.07
0.50	0.10	1.32	0.42	0.084	0.84	0.27	0.64	0.02
0.50	0.08	1.62	0.45	0.072	0.90	0.38	0.84	0.02
0.55	0.14	1.04	0.35	0.089	0.64	0.22	0.63	0.04
0.55	0.12	1.18	0.38	0.083	0.69	0.26	0.68	0.04
0.55	0.10	1.39	0.45	0.082	0.82	0.33	0.73	0.06
0.60	0.14	1.09	0.40	0.093	0.67	0.27	0.68	0.04
0.60	0.12	1.24	0.45	0.090	0.75	0.30	0.67	0.08

(Continued)

Table 5 (Concluded)

<u>d, ft</u>	<u>d/L</u>	<u>T, sec</u>	<u>H, ft</u>	<u>H/L</u>	<u>H/d</u>	<u>R<sub>u</sub>, ft</u>	<u>R<sub>u</sub>/H</u>	<u>Standard Deviation, ft</u>
<u>cot <math>\alpha</math> = 2.0 (Continued)</u>								
0.65	0.14	1.13	0.46	0.099	0.71	0.30	0.65	0.05
0.65	0.12	1.29	0.51	0.094	0.78	0.34	0.67	0.04
0.70	0.14	1.18	0.46	0.092	0.66	0.33	0.72	0.03
<u>cot <math>\alpha</math> = 3.0</u>								
0.40	0.14	0.89	0.27	0.094	0.68	0.13	0.48	0.06
0.40	0.12	1.01	0.33	0.099	0.83	0.18	0.55	0.02
0.40	0.10	1.18	0.36	0.090	0.90	0.21	0.58	0.03
0.40	0.08	1.45	0.37	0.074	0.93	0.23	0.62	0.03
0.40	0.06	1.90	0.42	0.063	1.05	0.28	0.67	0.07
0.40	0.04	2.82	0.42	0.042	1.05	0.28	0.67	0.02
0.45	0.14	0.94	0.31	0.097	0.69	0.15	0.48	0.04
0.45	0.12	1.07	0.33	0.088	0.73	0.18	0.55	0.03
0.45	0.10	1.26	0.39	0.087	0.87	0.21	0.54	0.07
0.45	0.08	1.54	0.44	0.078	0.98	0.26	0.59	0.03
0.45	0.06	2.02	0.46	0.061	1.02	0.33	0.72	0.03
0.50	0.14	0.99	0.30	0.084	0.60	0.16	0.53	0.03
0.50	0.12	1.13	0.41	0.098	0.82	0.20	0.49	0.02
0.50	0.10	1.32	0.42	0.084	0.84	0.23	0.55	0.04
0.50	0.08	1.62	0.45	0.072	0.90	0.27	0.60	0.04
0.55	0.14	1.04	0.35	0.089	0.64	0.18	0.51	0.05
0.55	0.12	1.18	0.38	0.083	0.69	0.22	0.58	0.09
0.55	0.10	1.39	0.45	0.082	0.82	0.31	0.69	0.04
0.55	0.08	1.70	0.54	0.078	0.98	0.38	0.70	0.02
0.60	0.14	1.09	0.40	0.093	0.67	0.22	0.55	0.04
0.60	0.12	1.24	0.45	0.090	0.75	0.26	0.58	0.06
0.60	0.10	1.45	0.52	0.087	0.87	0.34	0.65	0.02
0.65	0.14	1.13	0.46	0.099	0.71	0.26	0.57	0.02
0.65	0.12	1.29	0.51	0.094	0.78	0.30	0.59	0.02
0.70	0.14	1.18	0.46	0.092	0.66	0.30	0.65	0.04
0.70	0.12	1.34	0.55	0.094	0.79	0.36	0.65	0.02
0.75	0.14	1.22	0.44	0.082	0.59	0.27	0.61	0.02
0.75	0.12	1.38	0.55	0.088	0.73	0.35	0.64	0.03

Table 6  
 Values of Relative Runup ( $R_u/H$ ) for Dolos Armor Randomly Placed  
 on Breakwater Trunks and Subjected to Breaking Waves  
 with No Overtopping:  $\cot \alpha = 1.5, 2.0, \text{ and } 3.0$

<u>d, ft</u>	<u>d/L</u>	<u>T, sec</u>	<u>H, ft</u>	<u>H/L</u>	<u>H/d</u>	<u><math>R_u</math>, ft</u>	<u><math>R_u/H</math></u>	<u>Standard Deviation, ft</u>
<u><math>\cot \alpha = 1.5</math></u>								
0.40	0.08	1.45	0.37	0.074	0.93	0.25	0.68	0.05
0.40	0.06	1.90	0.42	0.063	1.05	0.32	0.76	0.00
0.40	0.04	2.82	0.42	0.042	1.05	0.30	0.71	0.04
0.45	0.14	0.94	0.31	0.097	0.69	0.18	0.58	0.05
0.45	0.10	1.26	0.39	0.087	0.87	0.27	0.69	0.04
0.45	0.08	1.54	0.44	0.078	0.98	0.34	0.77	0.03
0.45	0.06	2.02	0.46	0.061	1.02	0.35	0.76	0.00
0.50	0.14	0.99	0.30	0.084	0.60	0.20	0.67	0.06
0.50	0.10	1.32	0.42	0.084	0.84	0.28	0.67	0.04
0.50	0.08	1.62	0.45	0.072	0.90	0.37	0.82	0.04
0.55	0.14	1.04	0.35	0.089	0.64	0.23	0.66	0.02
0.55	0.12	1.18	0.38	0.083	0.69	0.28	0.74	0.04
0.55	0.08	1.70	0.54	0.078	0.98	0.42	0.78	0.06
0.60	0.14	1.09	0.40	0.093	0.67	0.28	0.70	0.06
0.65	0.14	1.13	0.46	0.099	0.71	0.31	0.67	0.04
0.65	0.12	1.29	0.51	0.094	0.78	0.39	0.76	0.03
0.65	0.08	1.85	0.60	0.074	0.92	0.58	0.97	0.03
0.70	0.14	1.18	0.46	0.092	0.66	0.33	0.72	0.02
0.75	0.08	1.99	0.70	0.075	0.93	0.65	0.93	0.03
0.80	0.10	1.67	0.66	0.083	0.83	0.56	0.85	0.04
0.85	0.10	1.73	0.71	0.084	0.84	0.61	0.86	0.03
0.90	0.10	1.78	0.77	0.086	0.86	0.61	0.79	0.02
<u><math>\cot \alpha = 2.0</math></u>								
0.40	0.08	1.45	0.37	0.074	0.93	0.25	0.68	0.04
0.40	0.06	1.90	0.42	0.063	1.05	0.31	0.74	0.03
0.40	0.04	2.82	0.42	0.042	1.05	0.28	0.67	0.04
0.45	0.14	0.94	0.31	0.097	0.69	0.17	0.55	0.02
0.45	0.10	1.26	0.39	0.087	0.87	0.24	0.62	0.04
0.45	0.08	1.54	0.44	0.078	0.98	0.31	0.70	0.03
0.45	0.06	2.02	0.46	0.061	1.02	0.35	0.76	0.03
0.50	0.14	0.99	0.30	0.084	0.60	0.19	0.63	0.05
0.50	0.10	1.32	0.42	0.084	0.84	0.26	0.62	0.04
0.50	0.08	1.62	0.45	0.072	0.90	0.35	0.78	0.04

(Continued)

Table 6 (Concluded)

<u>d, ft</u>	<u>d/L</u>	<u>T, sec</u>	<u>H, ft</u>	<u>H/L</u>	<u>H/d</u>	<u>R<sub>u</sub>, ft</u>	<u>R<sub>u</sub>/H</u>	<u>Standard Deviation, ft</u>
<u>cot <math>\alpha</math> = 2.0 (Continued)</u>								
0.55	0.14	1.04	0.35	0.089	0.64	0.23	0.66	0.03
0.55	0.12	1.18	0.38	0.083	0.69	0.26	0.68	0.02
0.55	0.08	1.70	0.54	0.078	0.98	0.38	0.70	0.03
0.60	0.14	1.09	0.40	0.093	0.67	0.25	0.63	0.04
0.65	0.14	1.13	0.46	0.099	0.71	0.25	0.54	0.02
0.65	0.12	1.29	0.51	0.094	0.78	0.32	0.63	0.02
0.70	0.14	1.18	0.46	0.092	0.66	0.29	0.63	0.05
0.80	0.12	1.43	0.55	0.082	0.69	0.42	0.76	0.03
0.85	0.14	1.30	0.56	0.092	0.66	0.40	0.71	0.04
0.85	0.12	1.47	0.63	0.089	0.74	0.46	0.73	0.03
0.95	0.14	1.37	0.61	0.090	0.64	0.41	0.67	0.02
0.95	0.12	1.56	0.66	0.083	0.69	0.50	0.76	0.01
<u>cot <math>\alpha</math> = 3.0</u>								
0.40	0.08	1.45	0.37	0.074	0.93	0.20	0.54	0.04
0.40	0.06	1.90	0.42	0.063	1.05	0.28	0.67	0.01
0.40	0.04	2.82	0.42	0.042	1.05	0.27	0.64	0.03
0.45	0.14	0.94	0.31	0.097	0.69	0.14	0.45	0.04
0.45	0.10	1.26	0.39	0.087	0.87	0.21	0.54	0.04
0.45	0.08	1.54	0.44	0.078	0.98	0.26	0.59	0.03
0.45	0.06	2.02	0.46	0.061	1.02	0.28	0.61	0.02
0.50	0.14	0.99	0.30	0.084	0.60	0.17	0.57	0.02
0.50	0.10	1.32	0.42	0.084	0.84	0.23	0.55	0.02
0.50	0.08	1.62	0.45	0.072	0.90	0.30	0.67	0.03
0.55	0.14	1.04	0.35	0.089	0.64	0.21	0.60	0.02
0.55	0.12	1.18	0.38	0.083	0.69	0.24	0.63	0.03
0.55	0.08	1.70	0.54	0.078	0.98	0.31	0.57	0.01
0.60	0.14	1.09	0.40	0.093	0.67	0.22	0.55	0.02
0.65	0.14	1.13	0.46	0.099	0.71	0.26	0.57	0.03
0.65	0.12	1.29	0.51	0.094	0.78	0.28	0.55	0.02
0.65	0.10	1.51	0.57	0.088	0.88	0.35	0.61	0.05
0.65	0.08	1.85	0.60	0.074	0.92	0.40	0.67	0.03
0.70	0.14	1.18	0.46	0.092	0.66	0.28	0.61	0.03
0.70	0.10	1.57	0.63	0.090	0.90	0.37	0.59	0.03
0.80	0.12	1.43	0.55	0.082	0.69	0.34	0.62	0.02
0.85	0.14	1.30	0.56	0.092	0.66	0.34	0.61	0.02
0.85	0.12	1.47	0.63	0.089	0.74	0.38	0.60	0.02
0.90	0.12	1.52	0.64	0.085	0.71	0.38	0.59	0.03
0.95	0.14	1.37	0.61	0.090	0.64	0.34	0.56	0.03
0.95	0.12	1.56	0.66	0.083	0.69	0.39	0.59	0.03

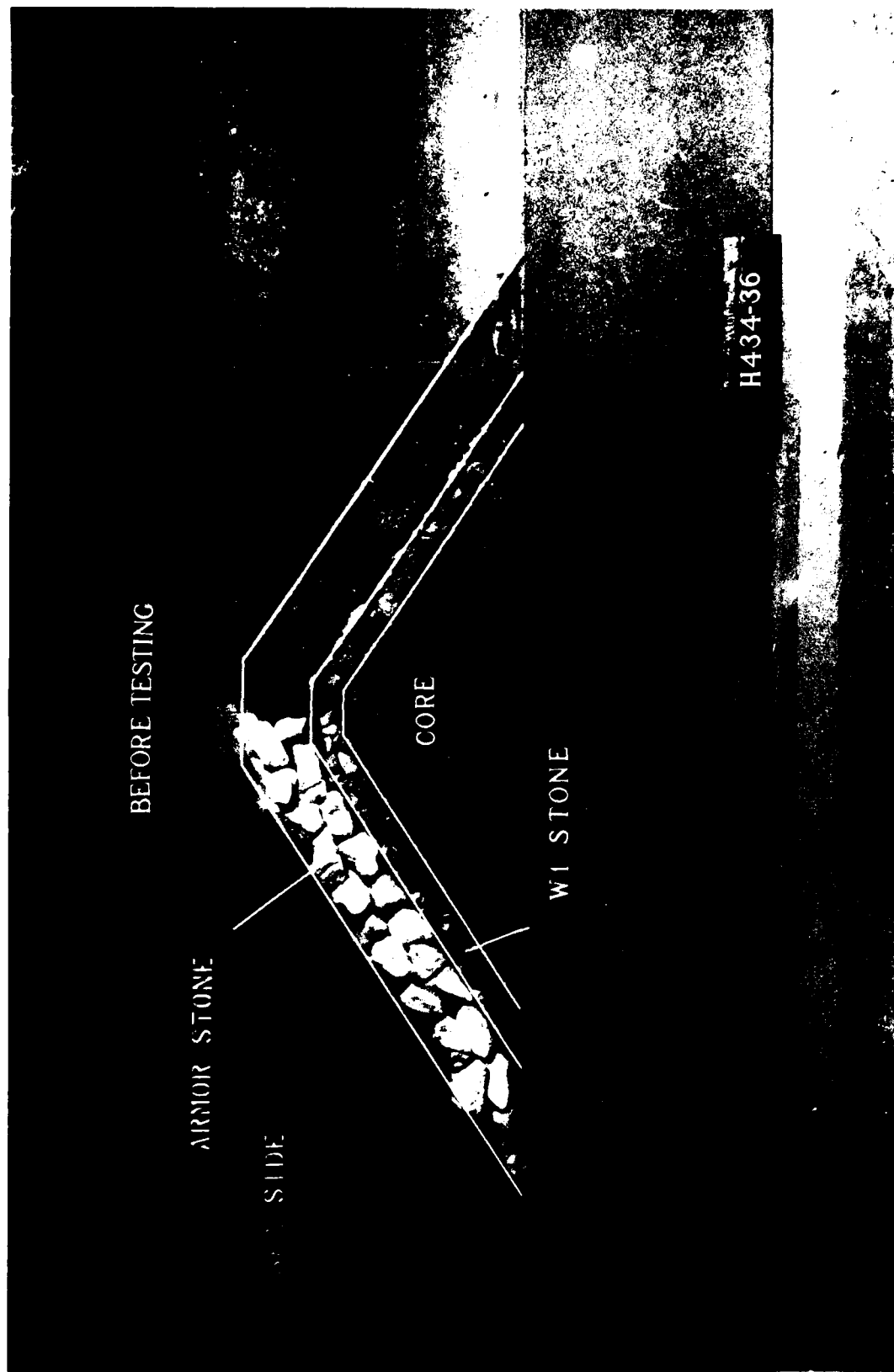


Photo 1. End view of a typical stone section before wave attack at a 1V-on-1.5H sea-side structure slope;  $W_a = 0.38 \text{ lb}$

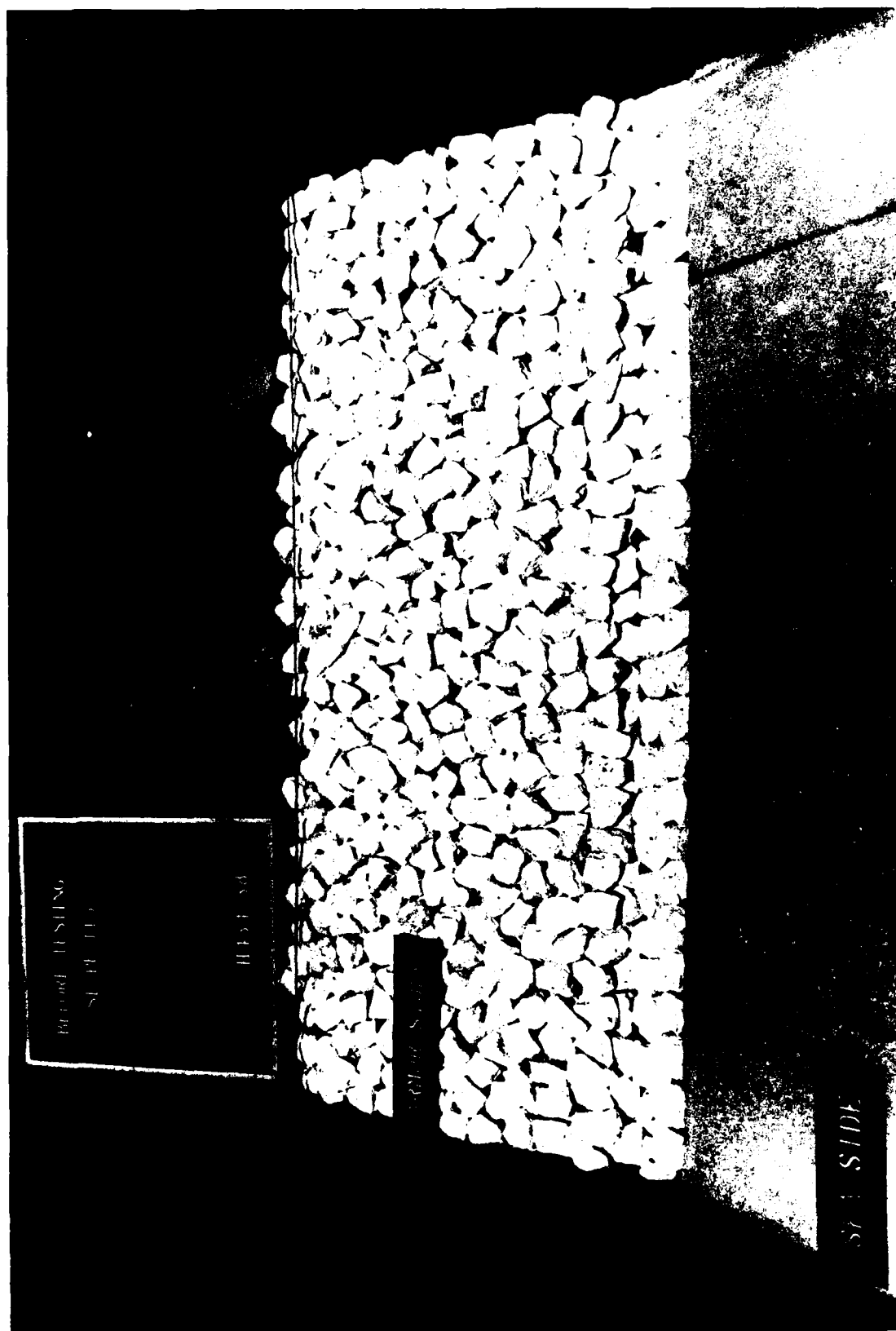


Photo 2. Sea-side view of a typical stone section before wave attack at a LV-on-1.5H sea-side structure slope;  $W_a = 0.38 \text{ lb}$

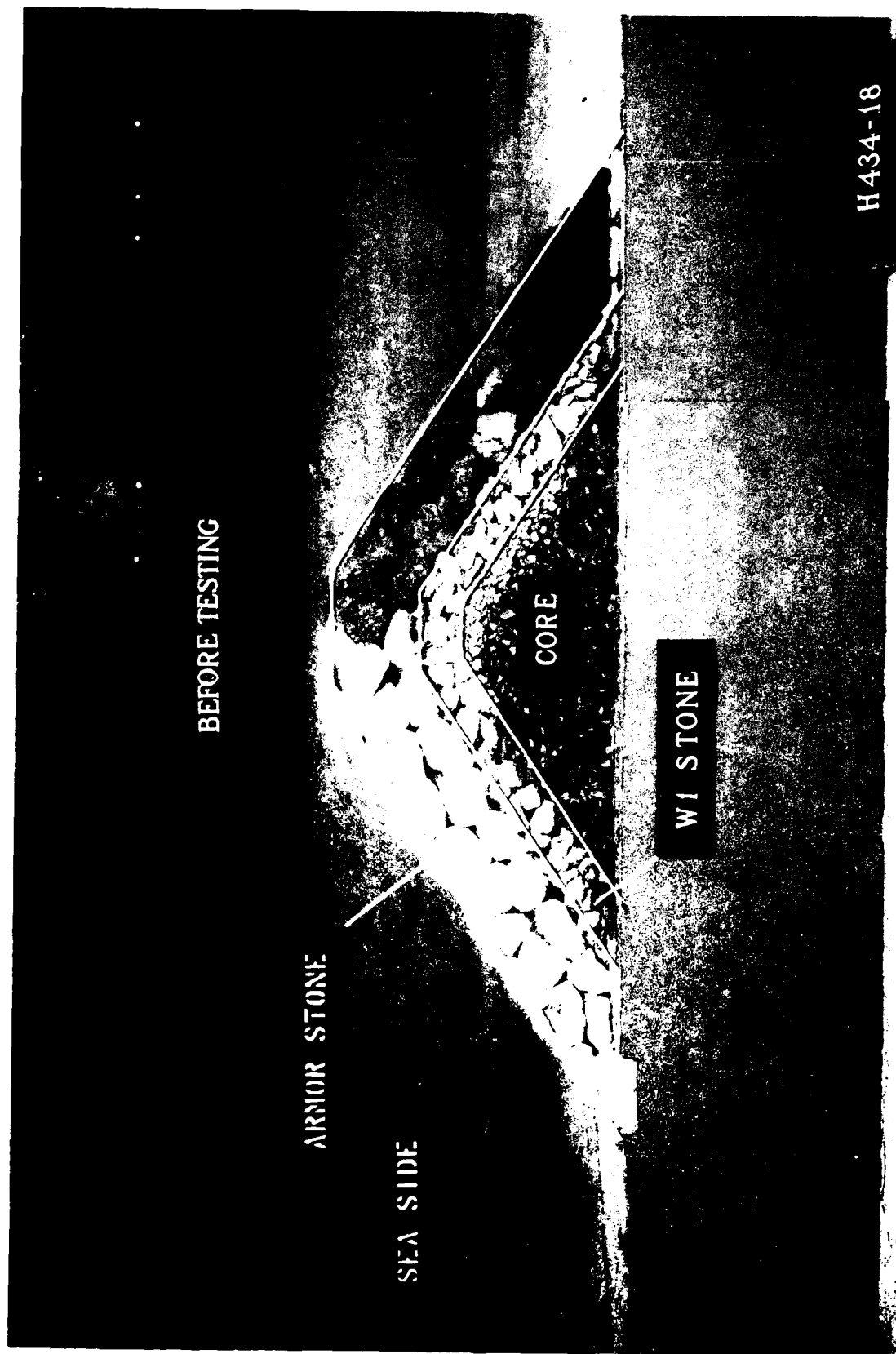


Photo 3. End view of a typical stone section before wave attack at a 1V-on-1.5H sea-side structure slope;  $W_a = 0.71 \text{ lb}$

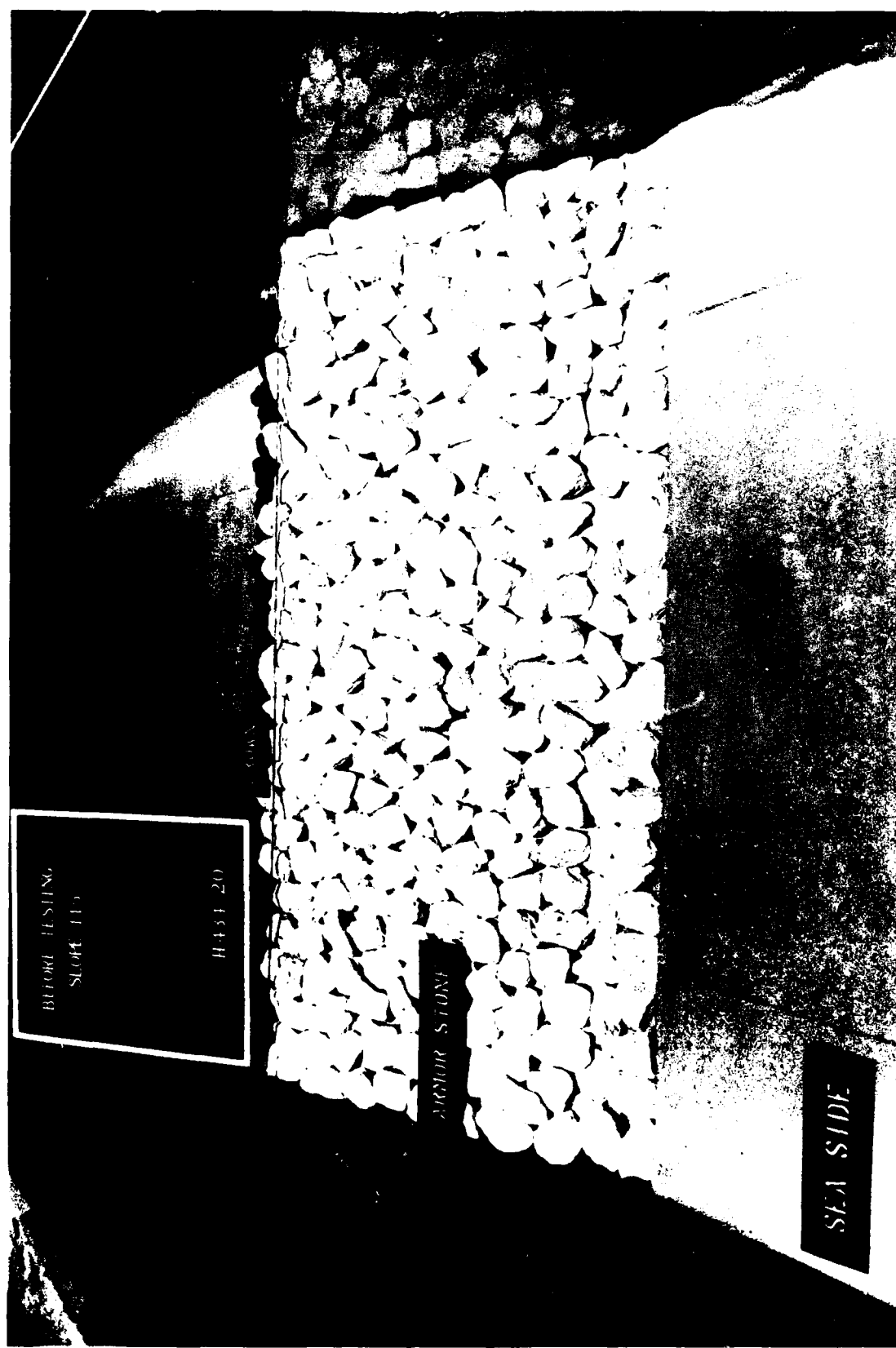


Photo 4. Sea-side view of a typical stone section before wave attack at a 1V-on-1.5H sea-side structure slope;  $W_a = 0.71 \text{ lb}$

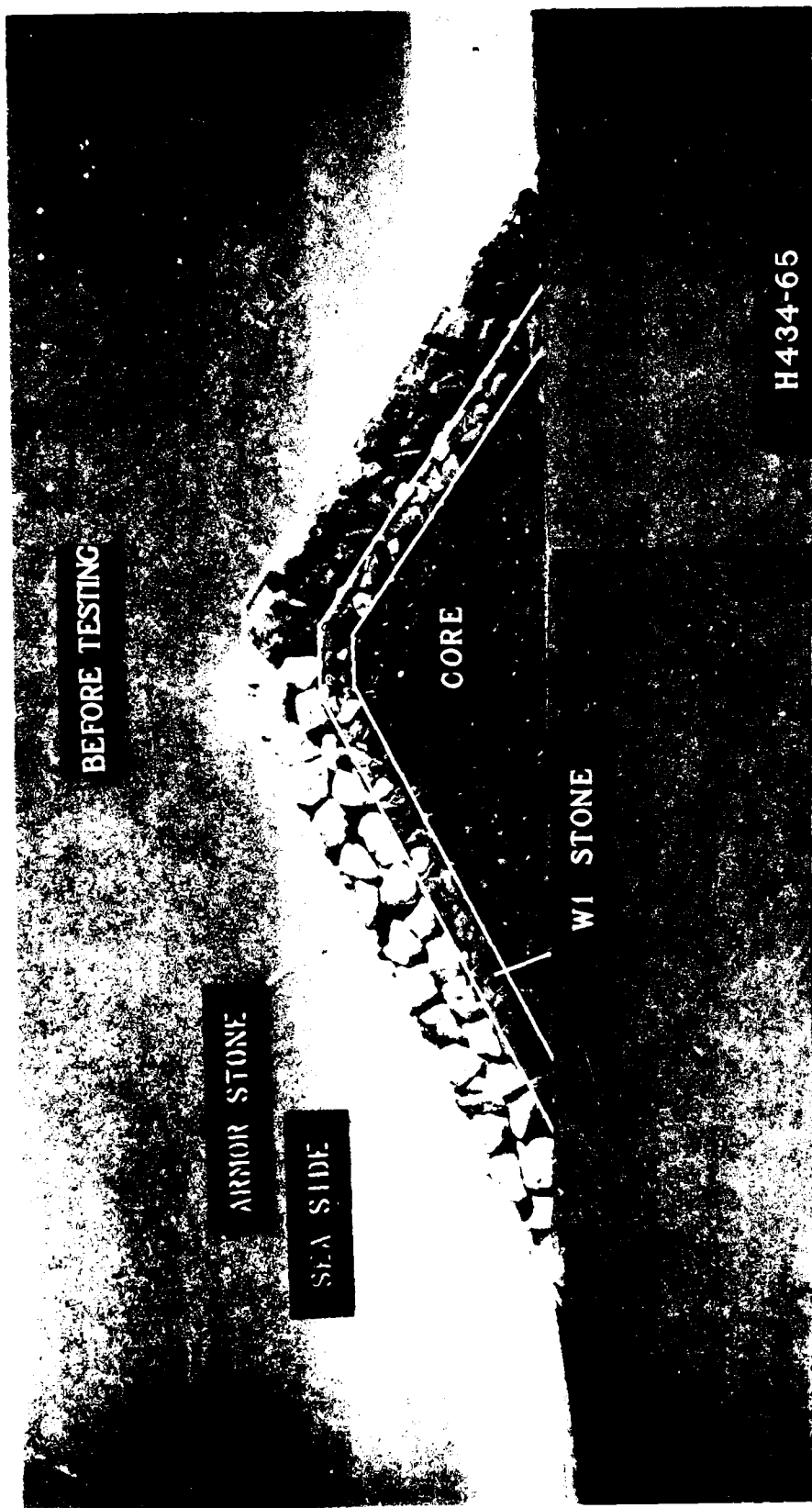


Figure 1. Cross section of typical stone section before wave attack at 1/4-on-1/4 sea-side structure slope of  $H_s = 0.30$  ft.

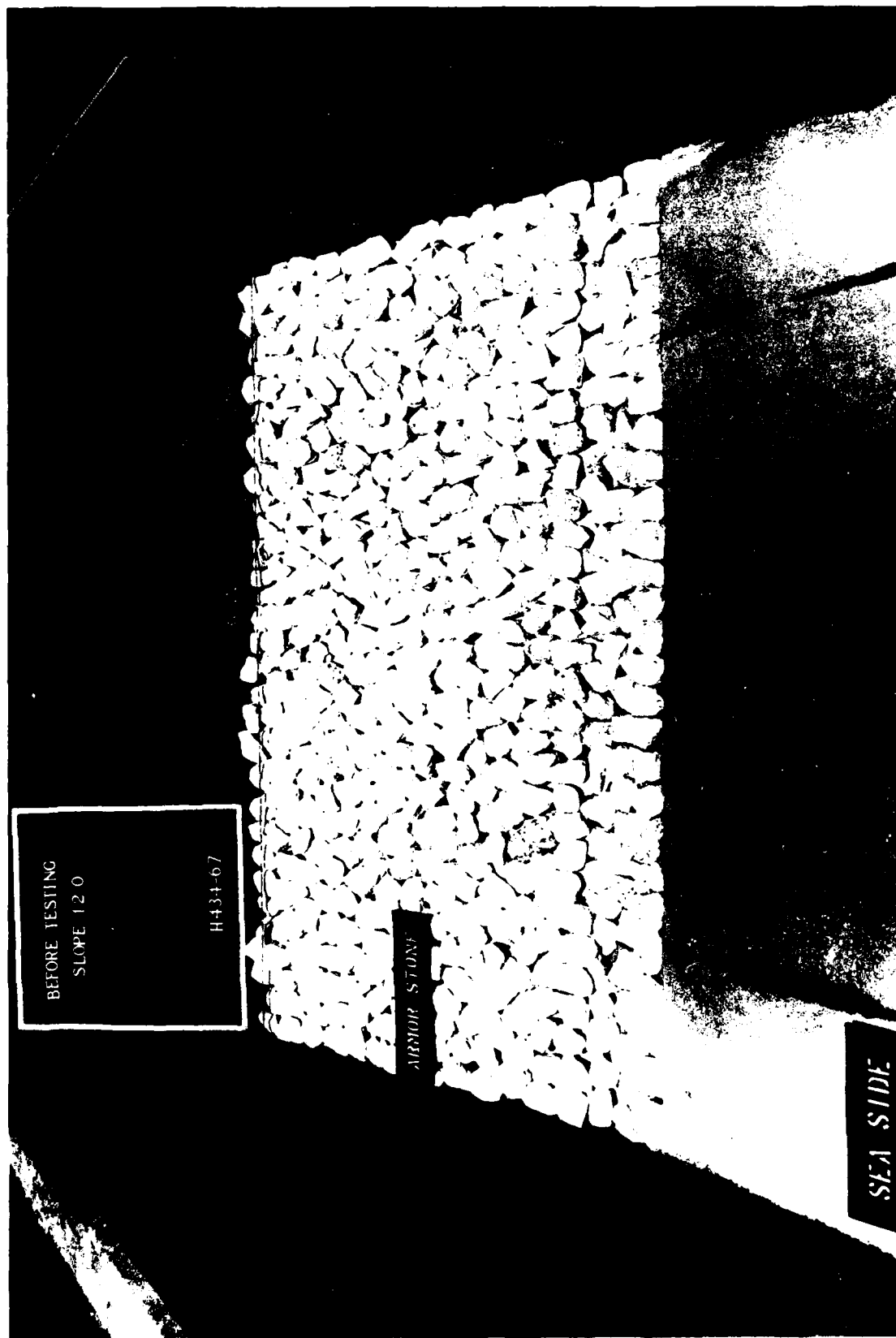


Photo 6. Sea-side view of a typical stone section before wave attack at a LV-on-2H sea-side structure slope;  $W_a = 0.38$  lb

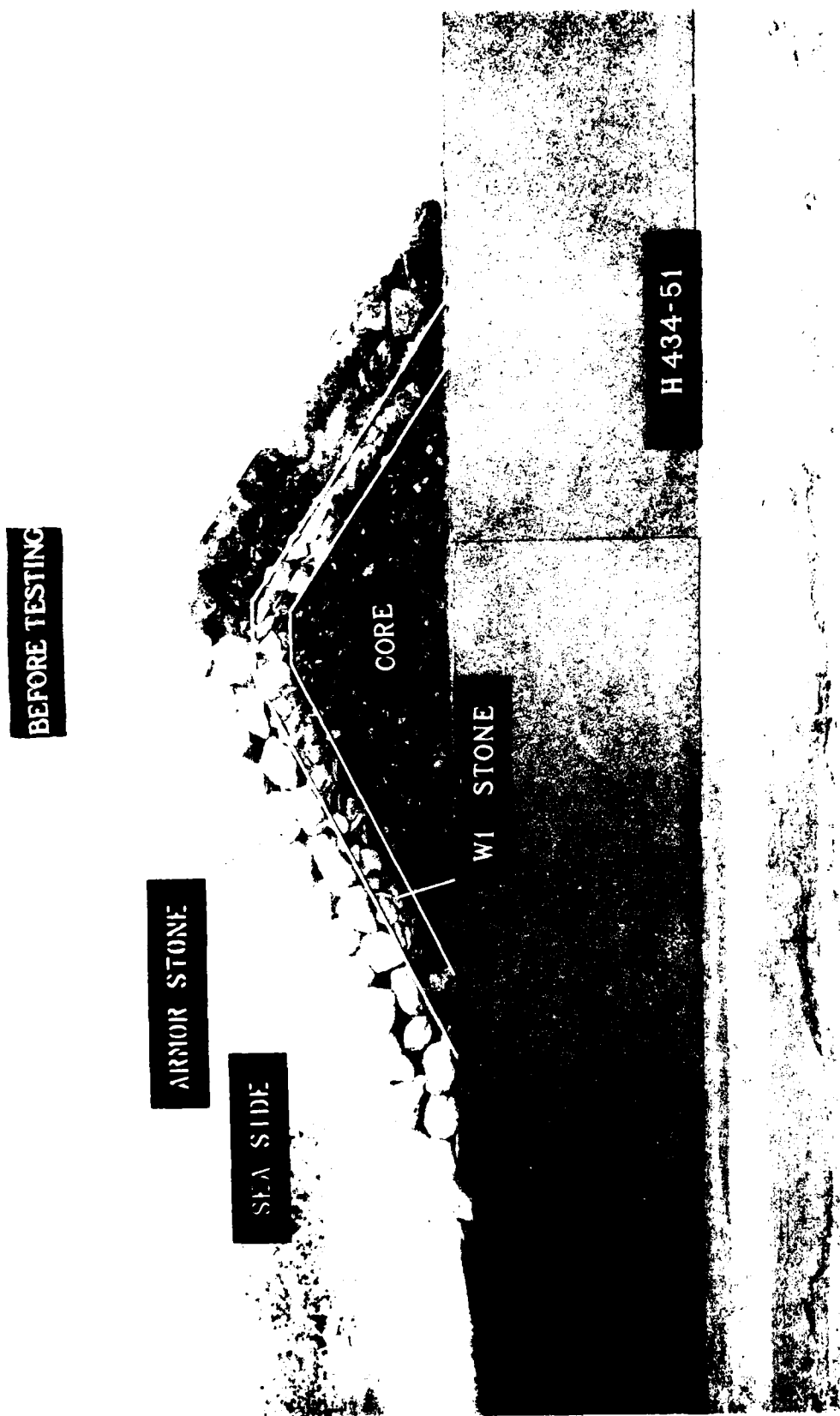


Photo 7. End view of a typical stone section before wave attack at a 1V-on-2H sea-side structure slope;  $W_a = 0.55 \text{ lb}$

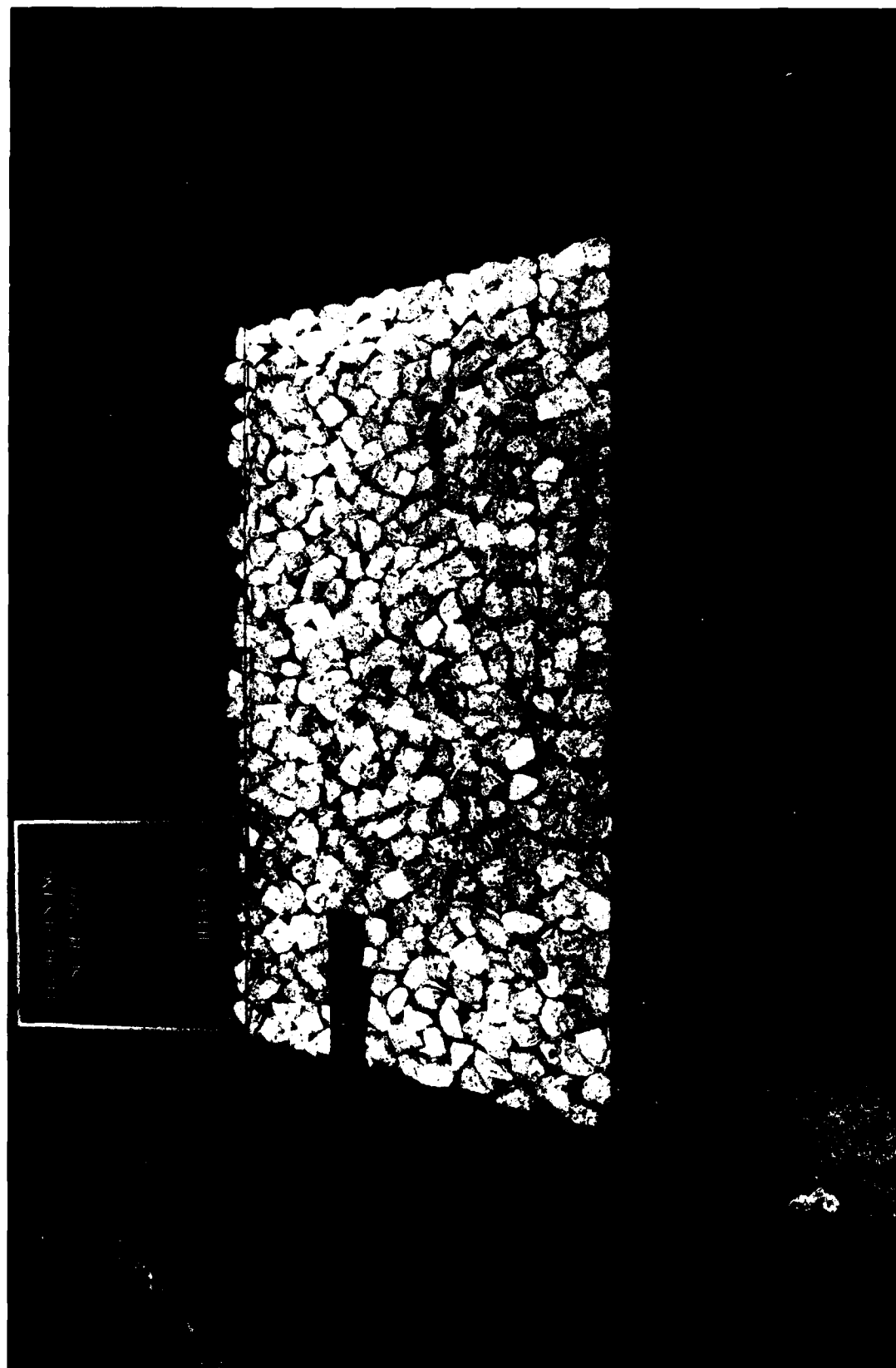


Photo 8. Sea-side view of a typical stone section before wave attack at a LV-on-2H sea-side structure slope;  $W_a = 0.55$  lb

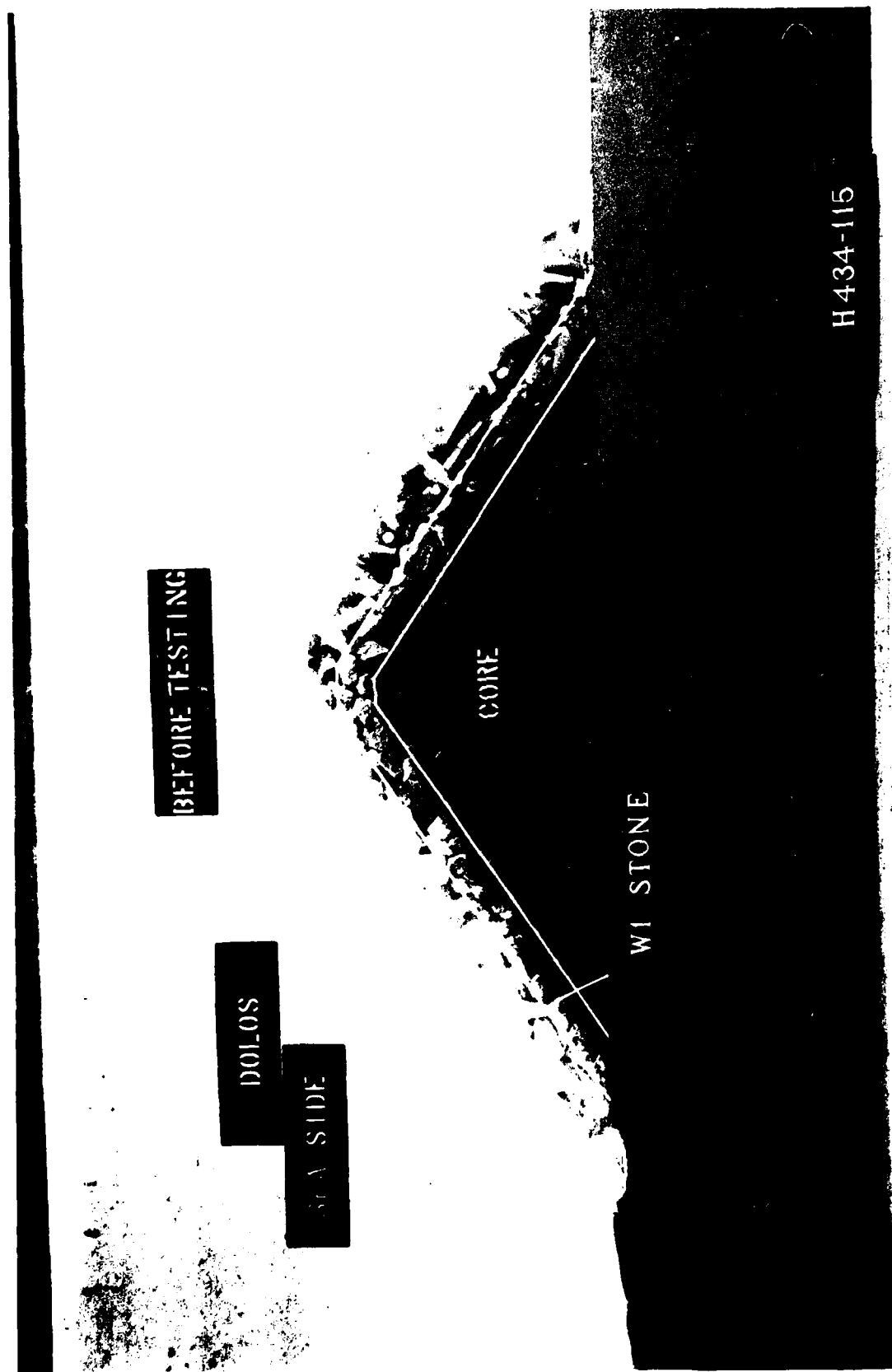


Photo 9. End view of a typical dolos section before wave attack at a 1V-on-1.5H sea-side structure slope;  $W_a = 0.276 \text{ lb}$

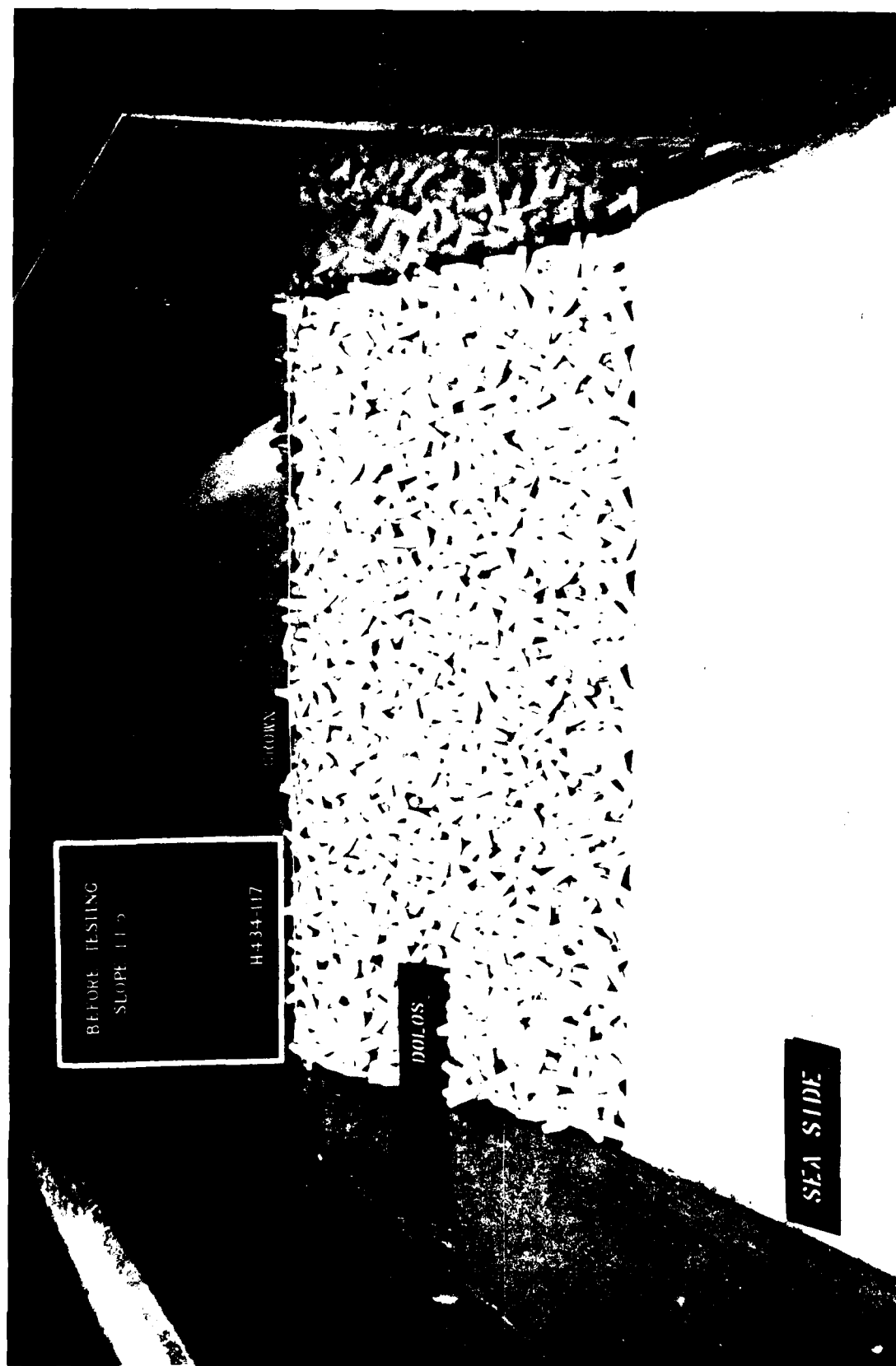


Photo 10. Sea-side view of a typical dolos section before wave attack at a LV-on-1.5H sea-side structure slope;  $W_a = 0.276 \text{ lb}$

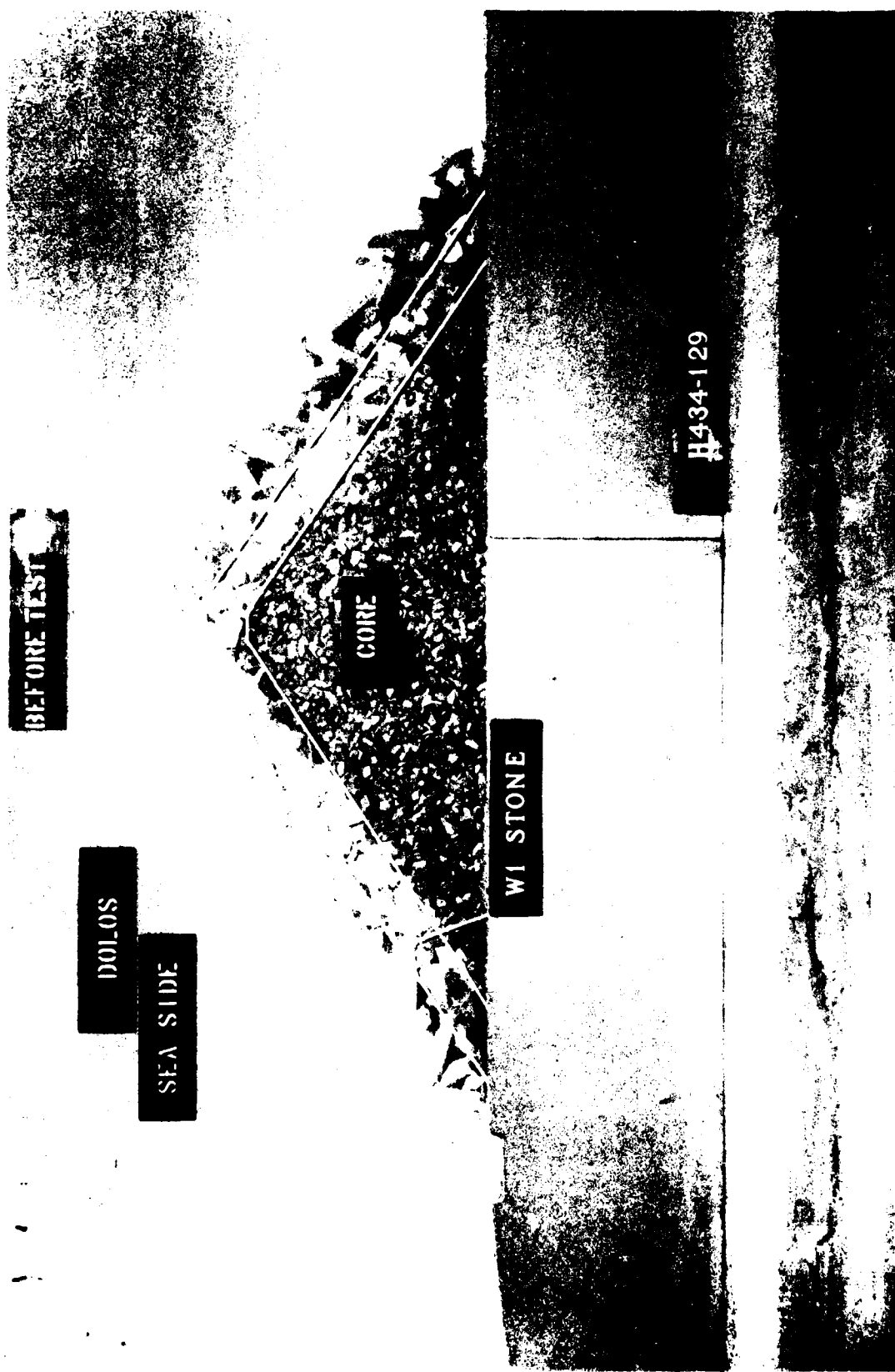


Photo 11. End view of a typical dolos section before wave attack at a LV-on-1.5H sea-side structure slope;  $W_a = 0.589$  lb

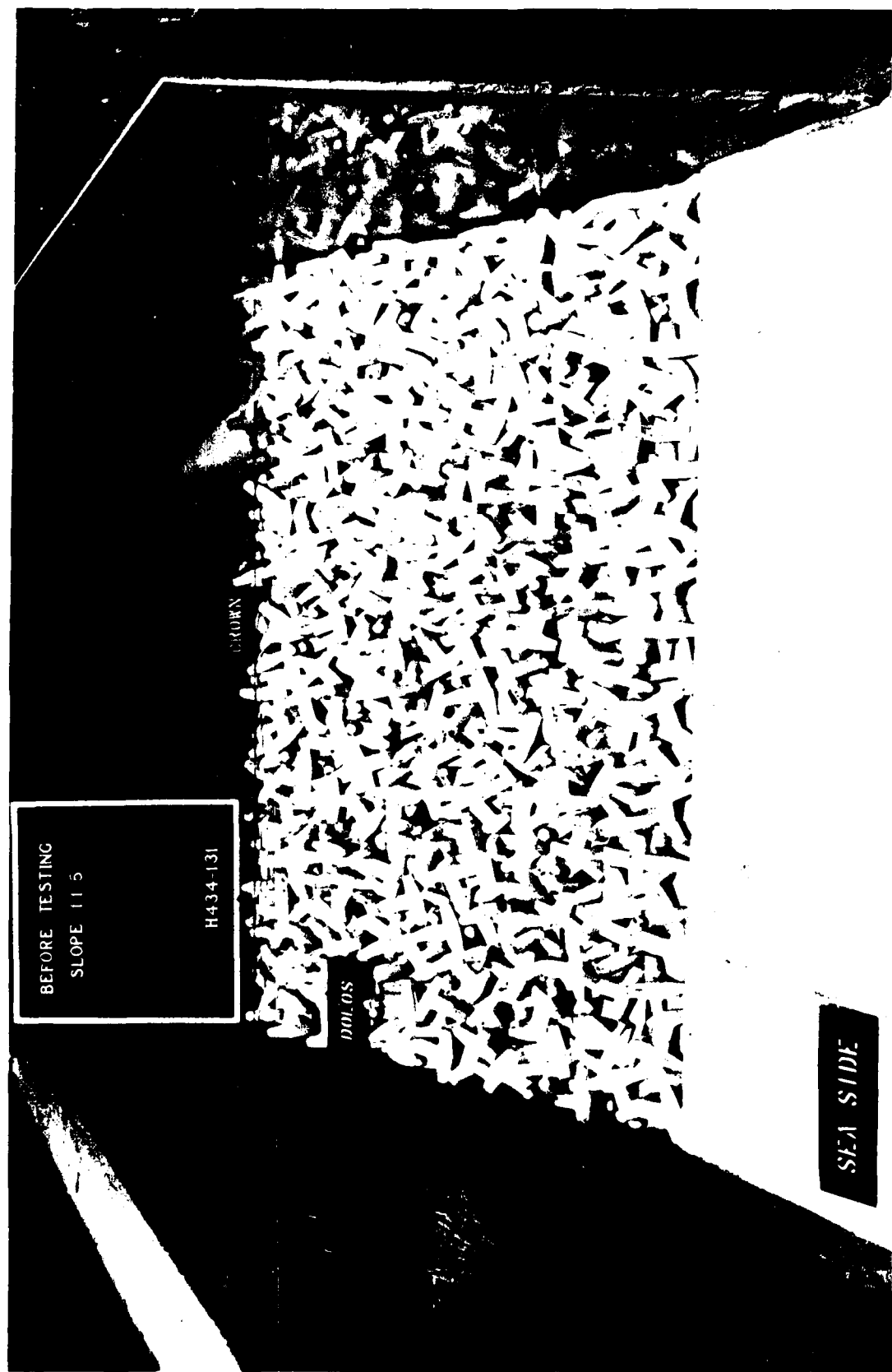


Photo 12. Sea-side view of a typical dolos section before wave attack at a 1V-on-1.5H sea-side structure slope;  $W_a = 0.589 \text{ lb}$

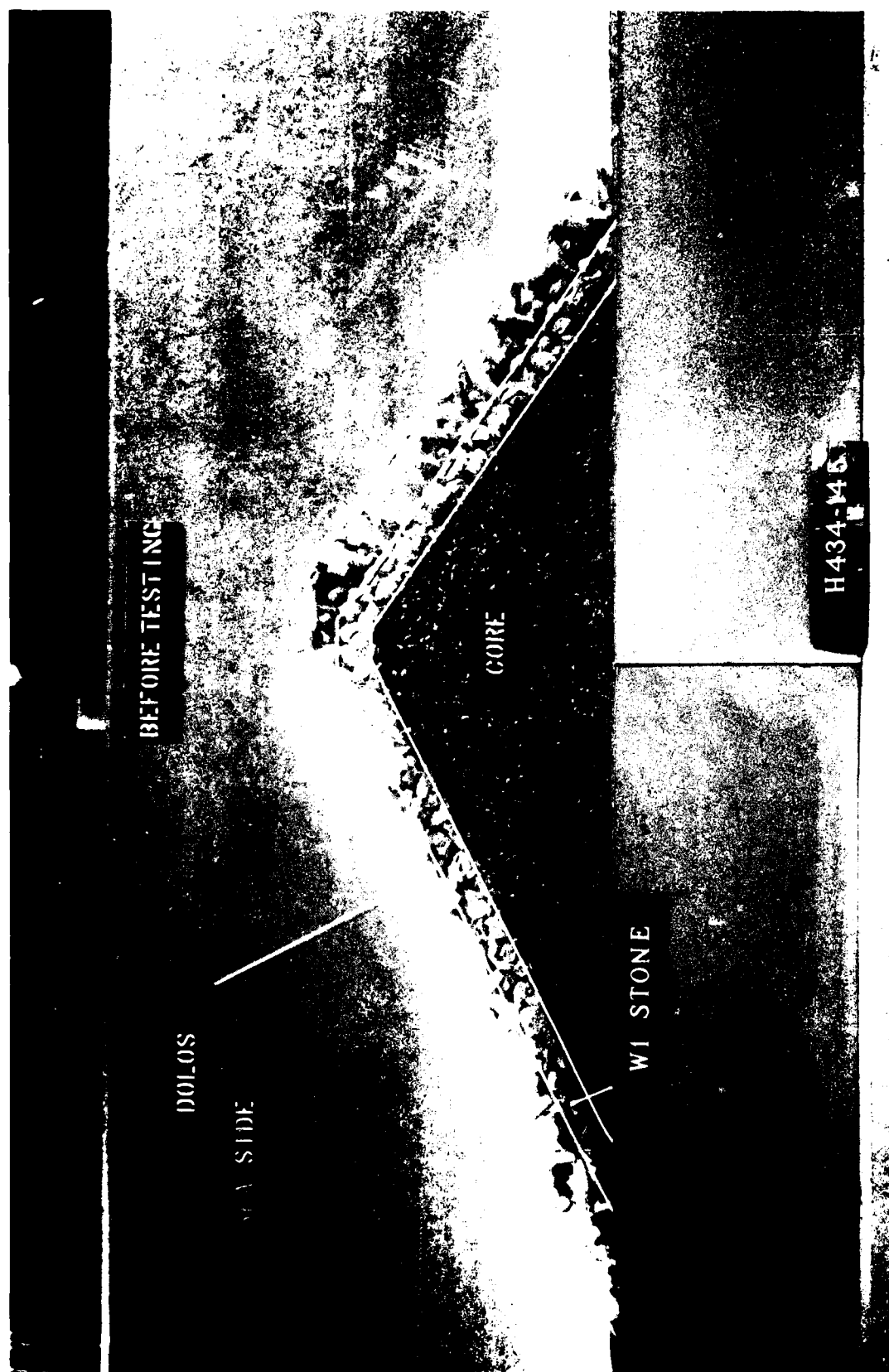


Photo 13. End view of a typical dolos section before wave attack at a 1V-on-2H sea-side structure slope;  $W_a = 0.276 \text{ lb}$

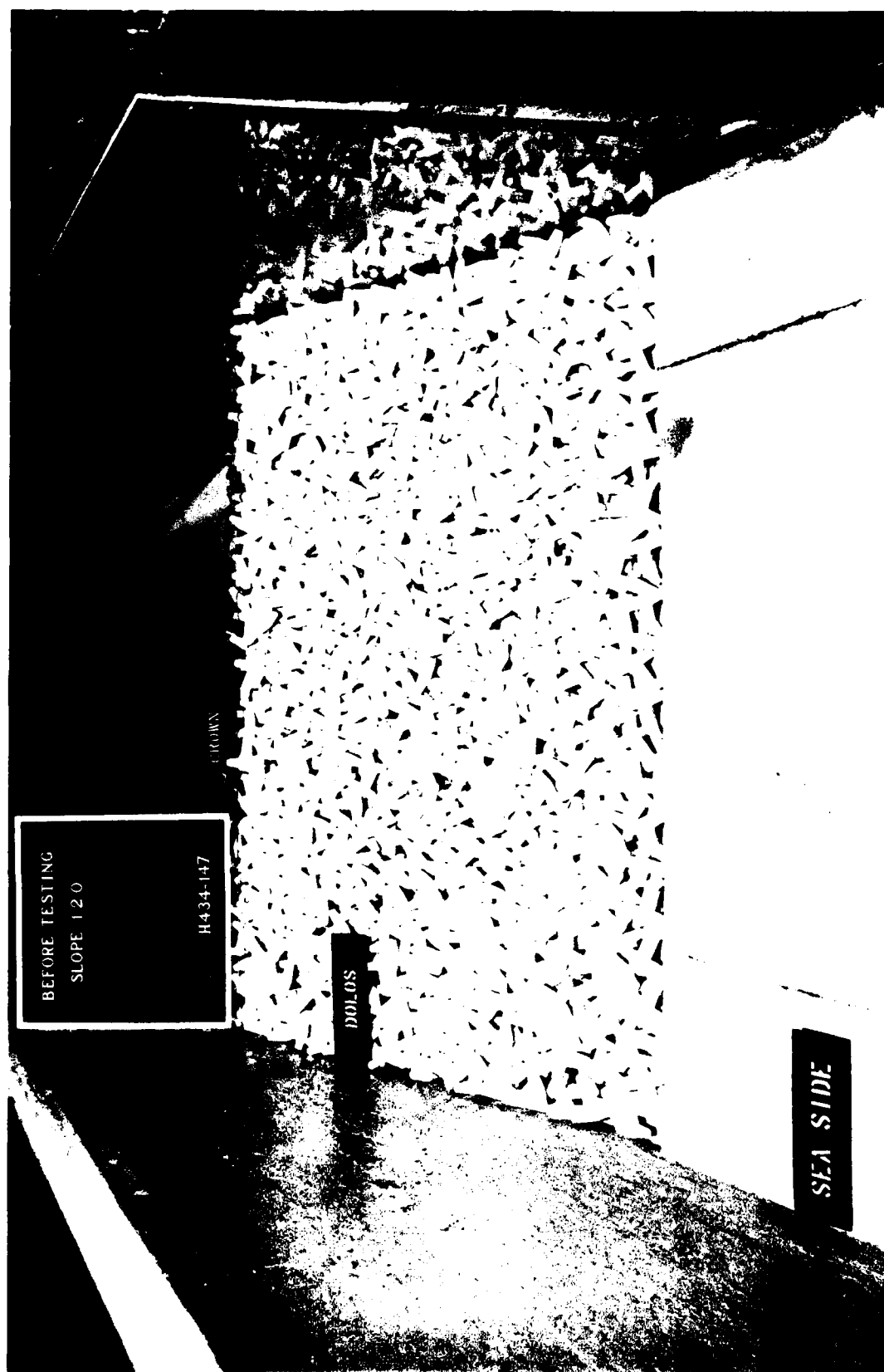


Photo 14. Sea-side view of a typical dolos section before wave attack at a LV-on-2H sea-side structure slope;  $W_a = 0.276$  lb

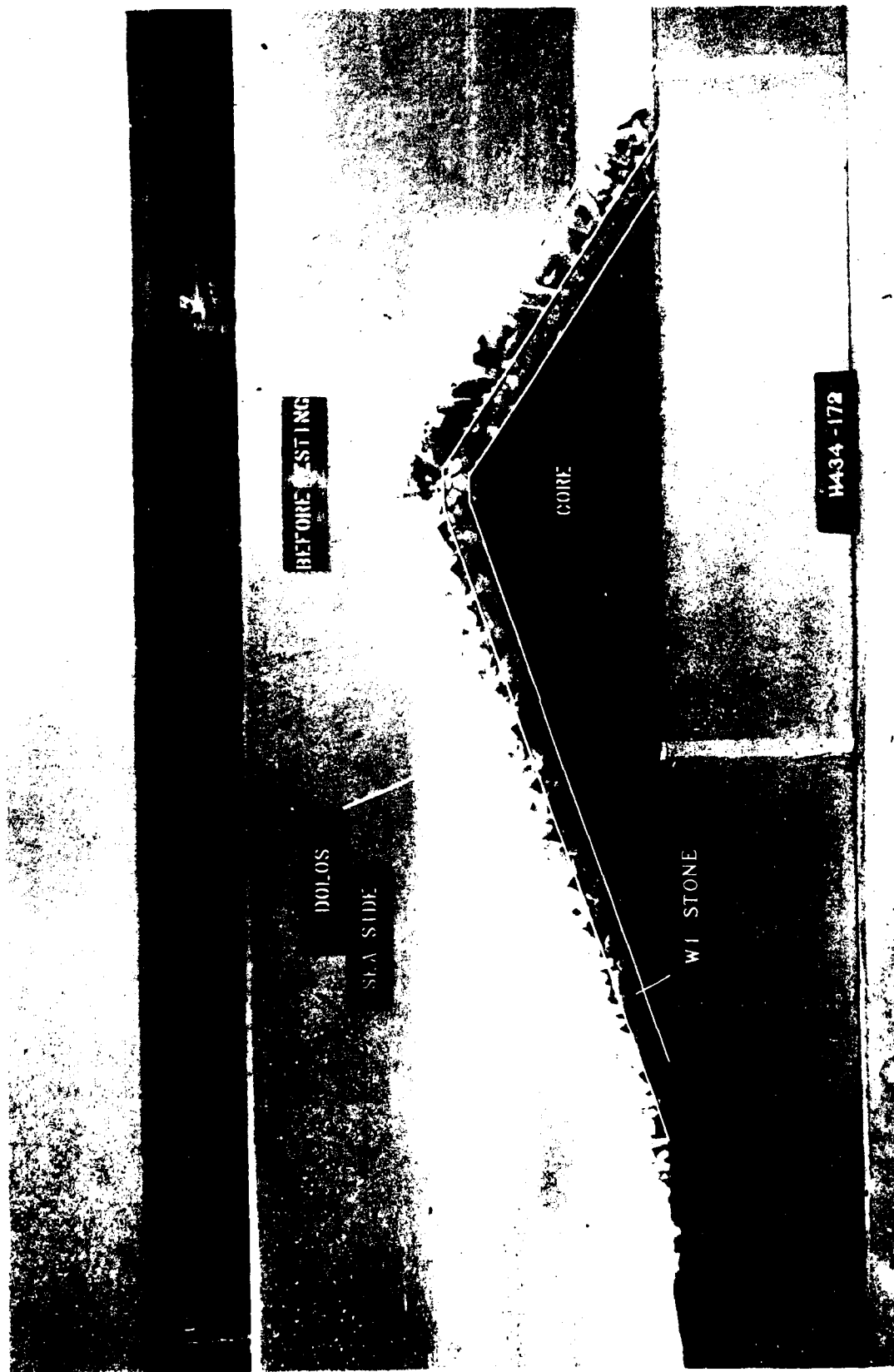


Photo 15. End view of a typical dolos section before wave attack at a LV-on-3H sea-side structure slope;  $W_a = 0.276$  lb

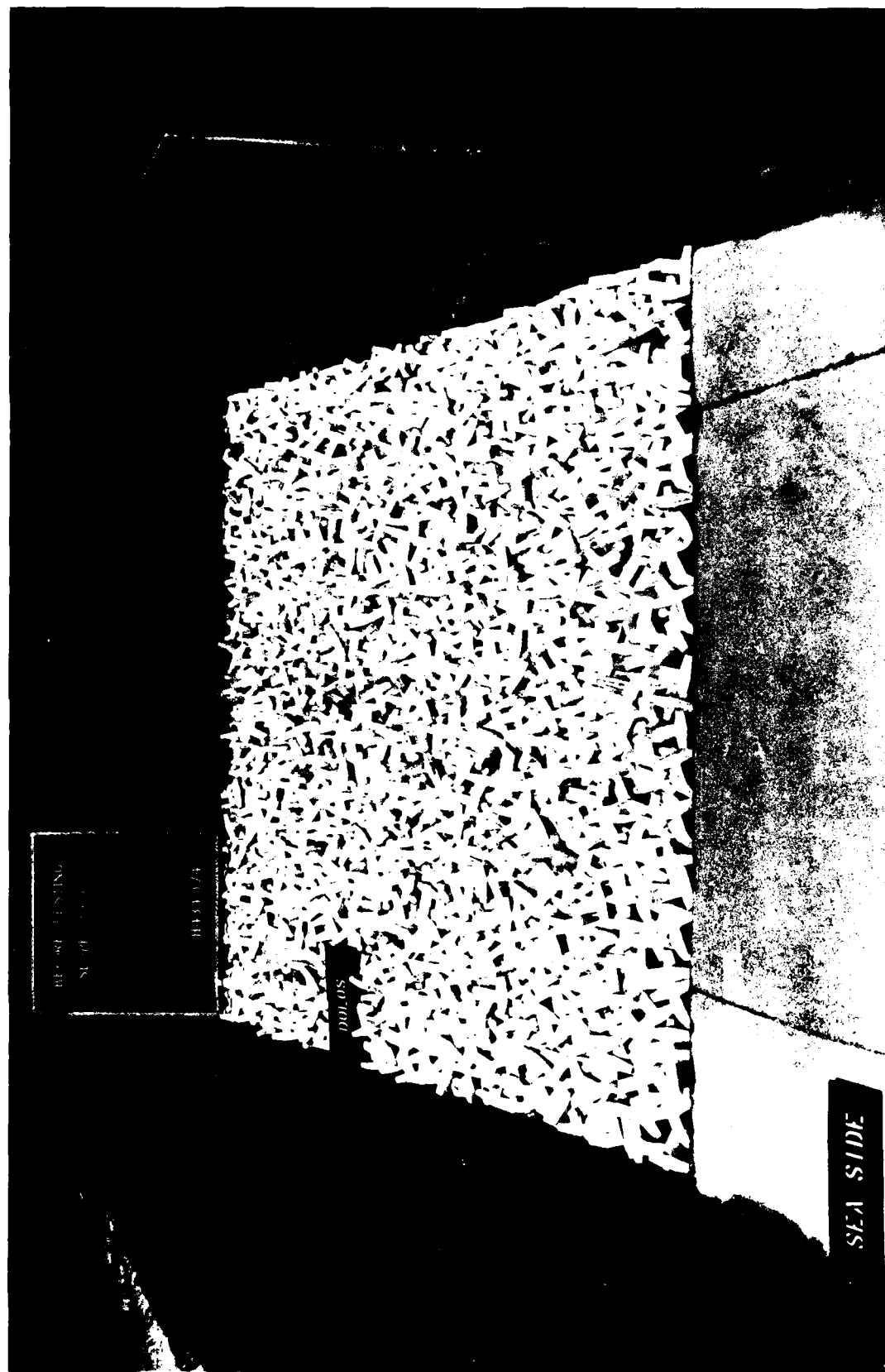


Photo 16. Sea-side view of a typical dolos section before wave attack at a 1V-on-3H sea-side structure slope;  $W_a = 0.276 \text{ lb}$

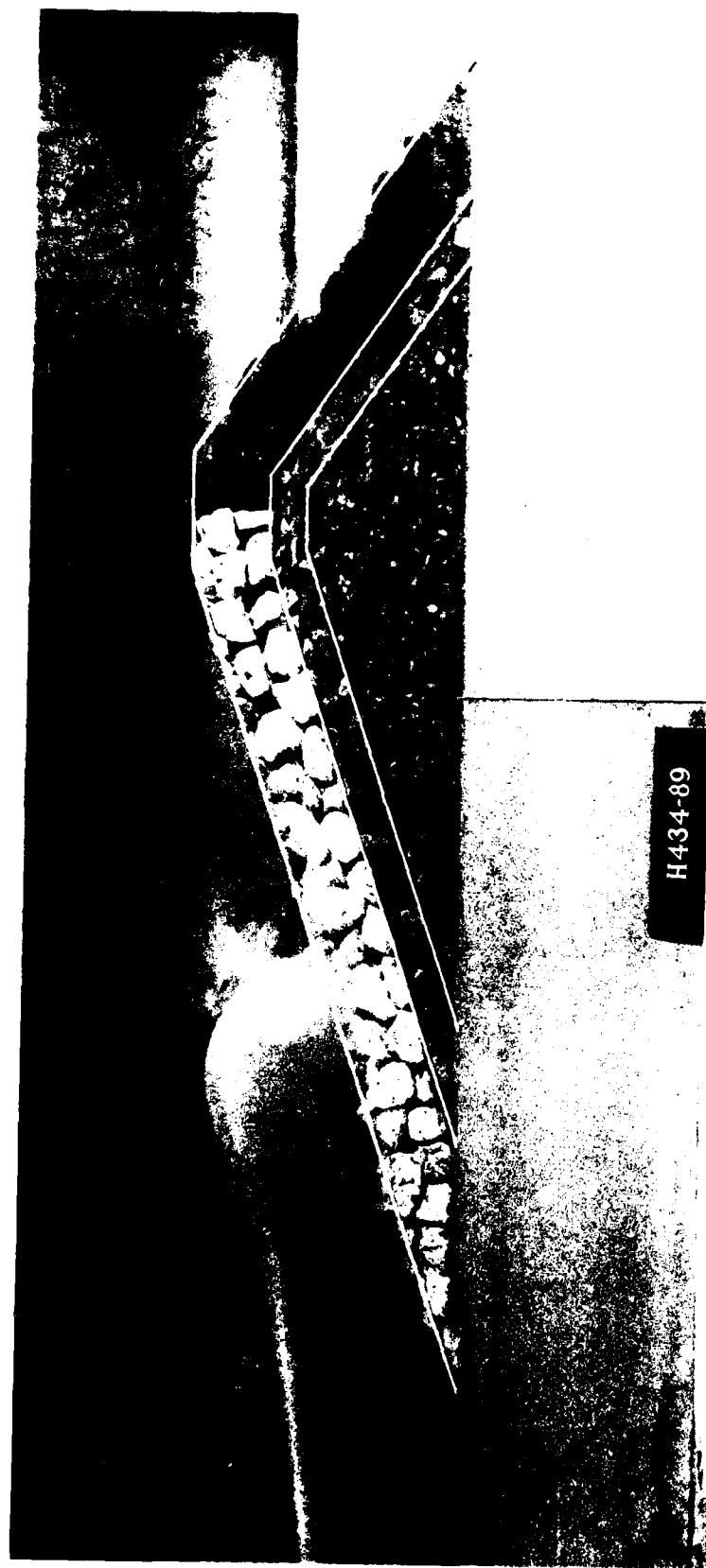


Photo 17. End view of a 1.38-sec, 0.55-ft wave breaking on a 1V-on-3H sea-side structure slope;  $d = 0.75$  ft; stone armor



H434-90

Photo 18. End view of runup produced by a 1.38-sec, 0.55-ft wave on a 1V-on-3H sea-side structure slope;  $d = 0.75$  ft; stone armor



Photo 19. End view of a 1.37-sec, 0.61-ft wave breaking on a 1V-on-2H sea-side structure slope;  $d = 0.95$  ft; dolos armor

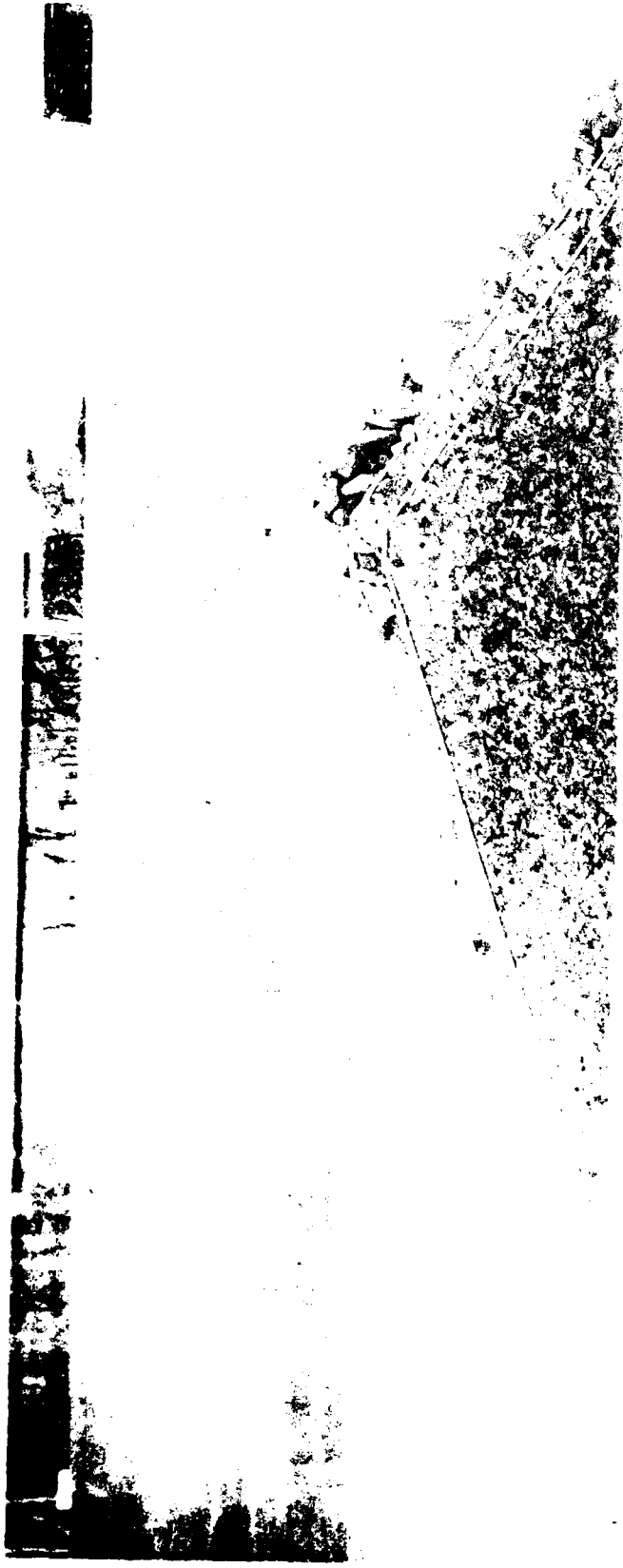


Photo 20. End view of runup produced by a 1.37-sec, 0.61-ft wave on a LV-on-2H sea-side structure slope;  $d = 0.95$  ft; dolos armor



H434-180

Photo 21. End view of a 1.52-sec, 0.64-ft wave breaking on a 1V-on-3H sea-side structure slope;  $d = 0.90$  ft; dolos armor



H434 -181A

Photo 22. End view of runup produced by a 1.52-sec, 0.64-ft wave on a 1V-on-3H sea-side structure slope;  $d = 0.90$  ft; dolos armor



AFTER TESTING  
SLOPE 1:1  
D-0.45 FT  
T-1.07 SEC  
H-0.33 FT

H434-39

ARMOR STONE

SIDE

SEA SIDE

Photo 23. Sea-side view after attack of 1.07-sec, 0.33-ft waves;  $d = 0.45$  ft;  $W_a = 0.38$  lb;  
IV-on-1.5H structure slope; stone armor

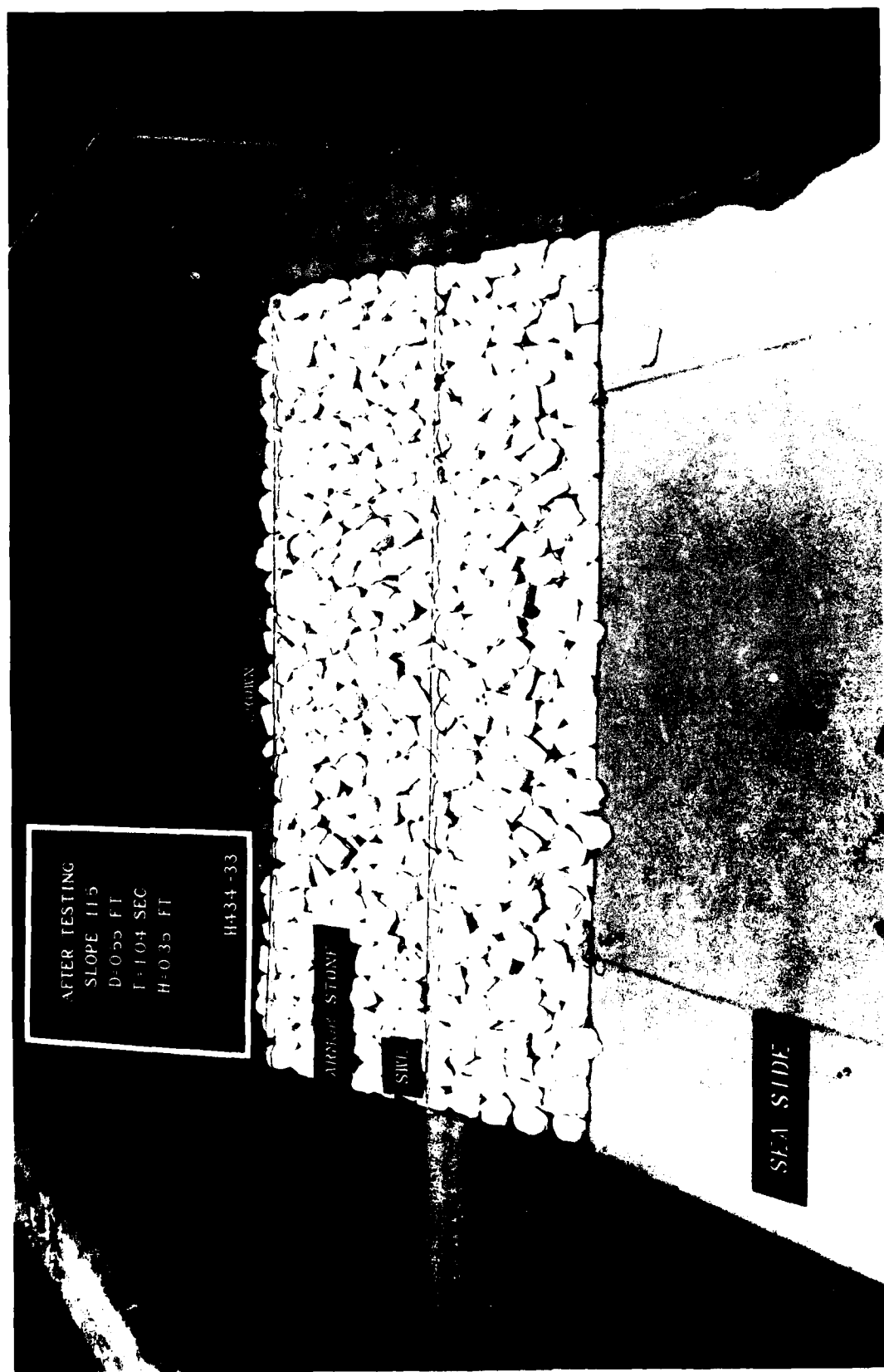


Photo 24. Sea-side view after attack of 1.04-sec, 0.35-ft waves;  $d = 0.55$  ft;  $W_a = 0.38$  lb;  
 1V-on-1.5H structure slope; stone armor

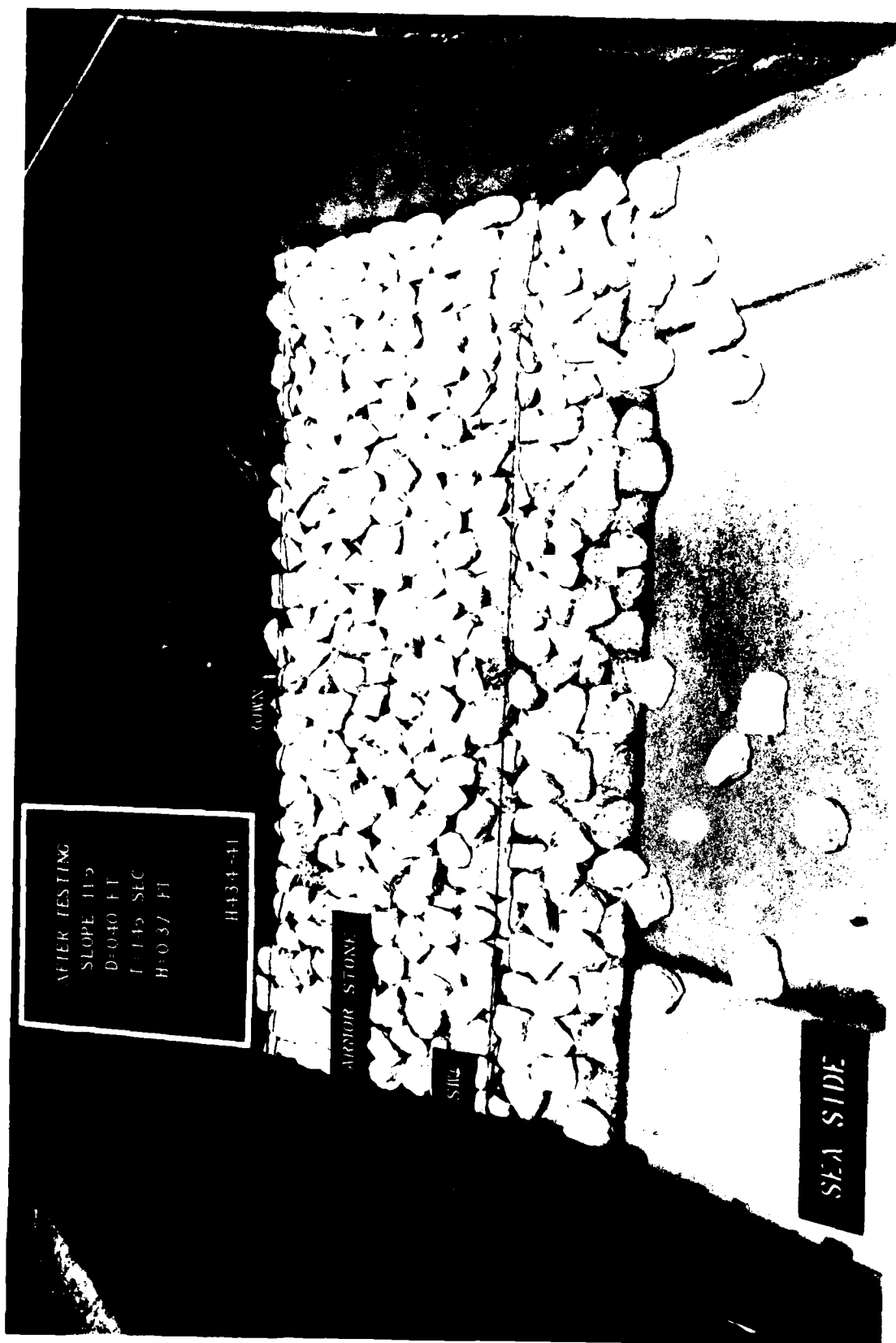


Photo 25. Sea-side view after attack of 1.45-sec, 0.37-ft waves;  $d = 0.40$  ft;  $W_a = 0.55$  lb; 1V-on-1.5H structure slope; stone armor



Photo 26. Sea-side view after attack of 1.18-sec, 0.38-ft waves;  $d = 0.55$  ft;  $W_a = 0.55$  lb; 1V-on-1.5H structure slope; stone armor

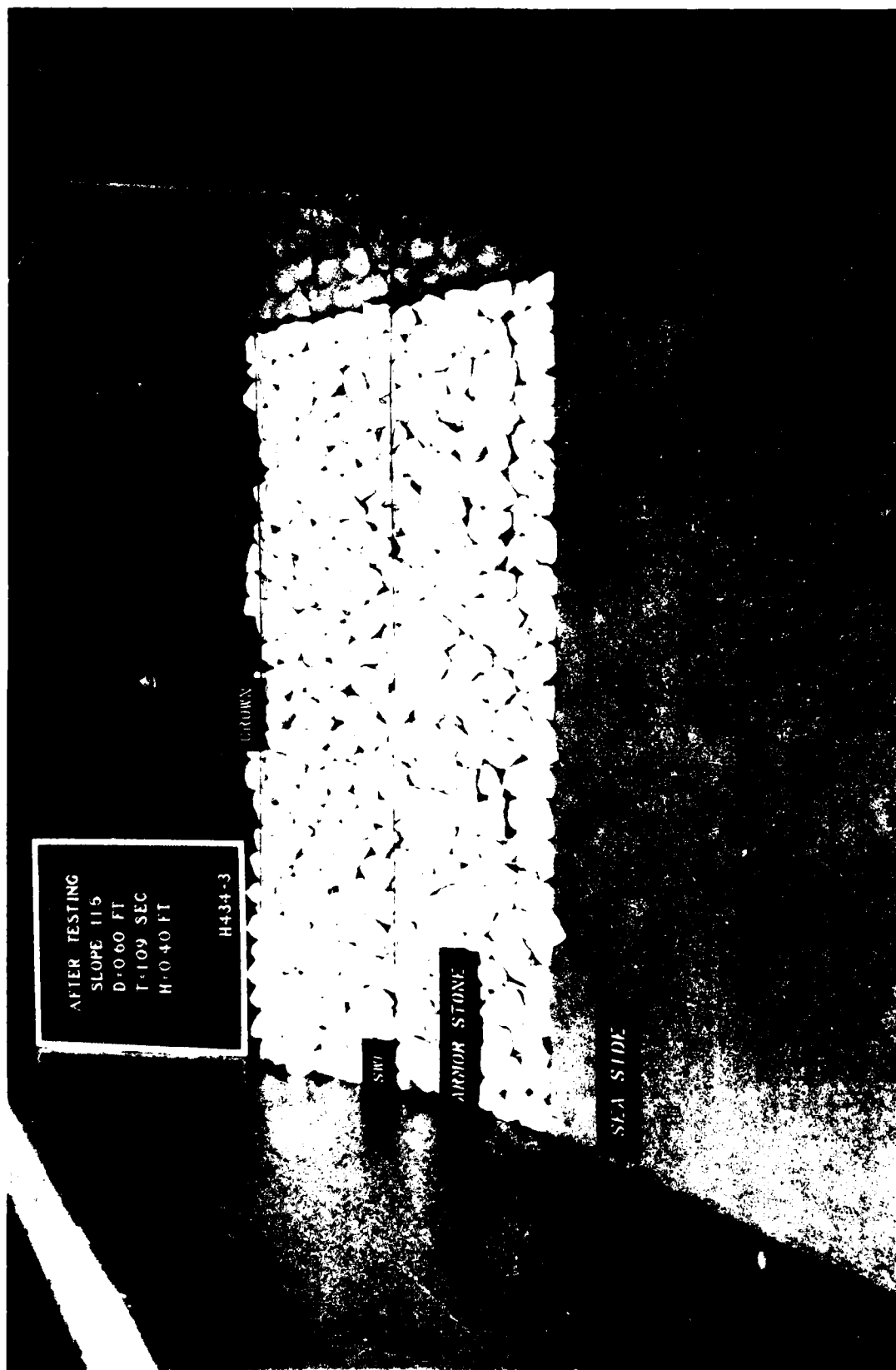


Photo 27. Sea-side view after attack of 1.09-sec, 0.40-ft waves,  $d = 0.60$  ft;  $W_a = 0.55$  lb; 1V-on-1.5H structure slope; stone armor

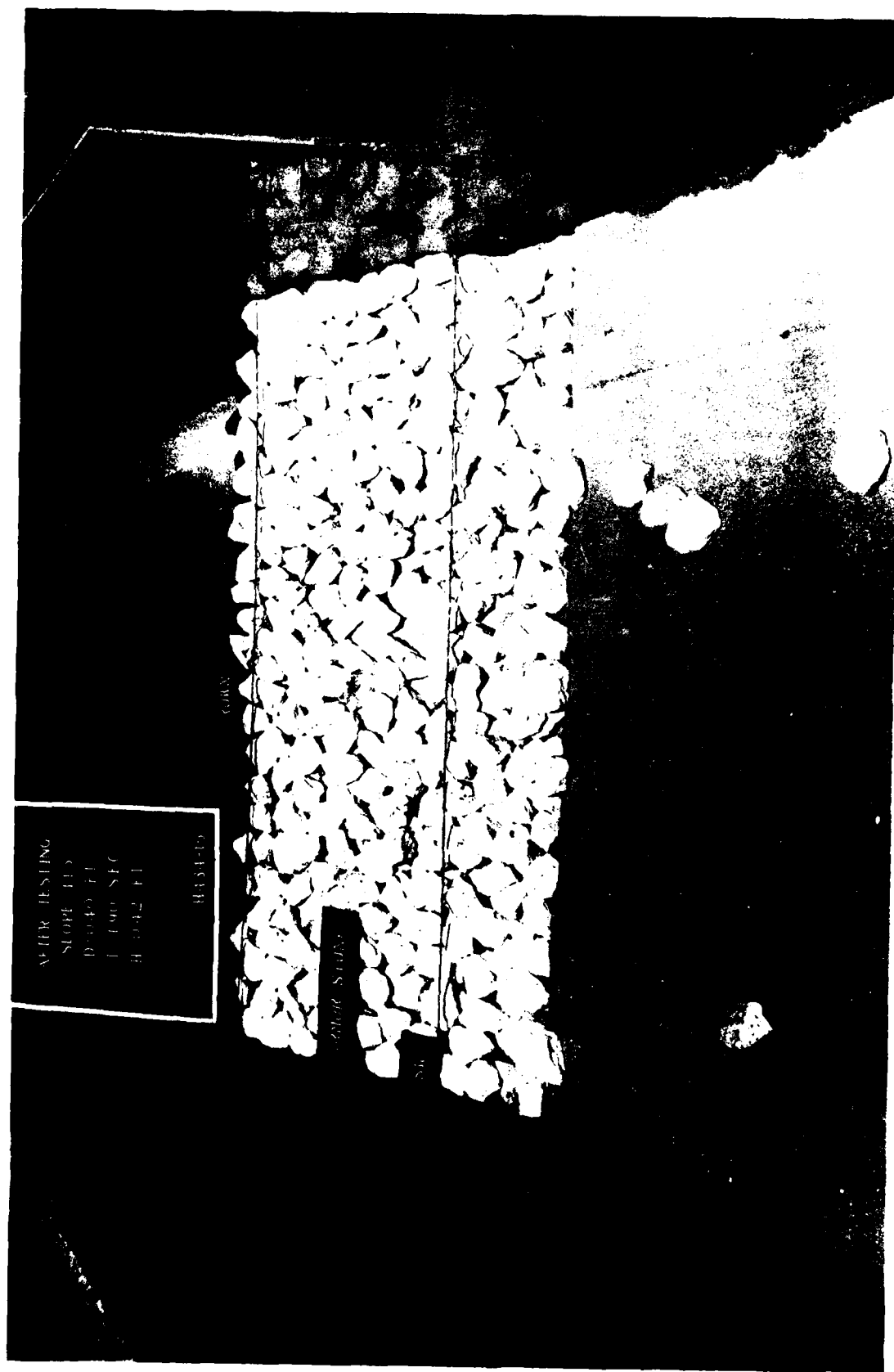


Photo 28. Sea-side view after attack of 1.90-sec, 0.42-ft waves;  $d = 0.40$  ft;  $W_a = 0.71$  lb;  
IV-on-1.5H structure slope; stone armor

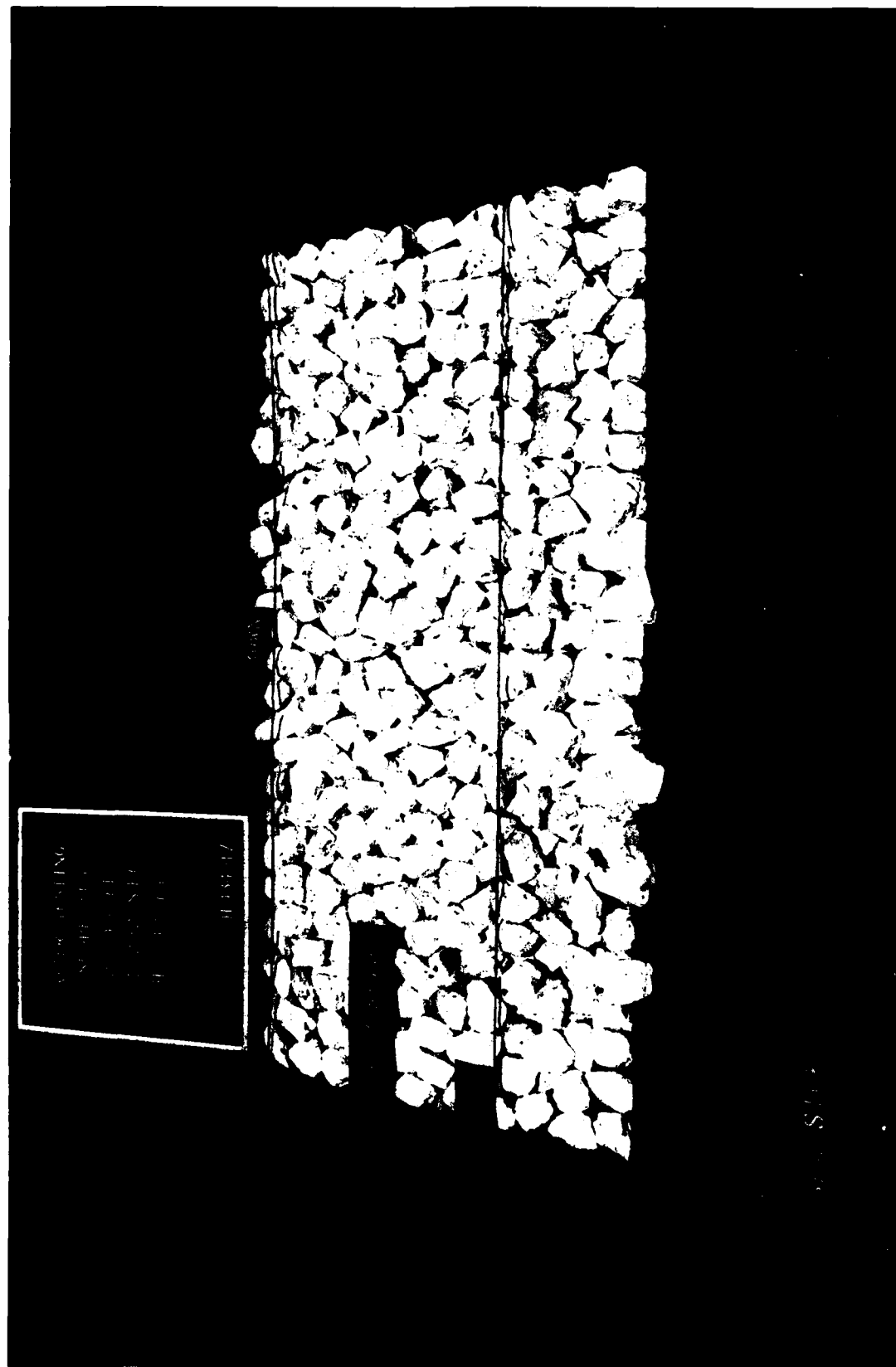


Photo 29. Sea-side view after attack of 2.82-sec, 0.42-ft waves;  $d = 0.40$  ft;  $W_a = 0.71$  lb;  
IV-on-1.5H structure slope; stone armor

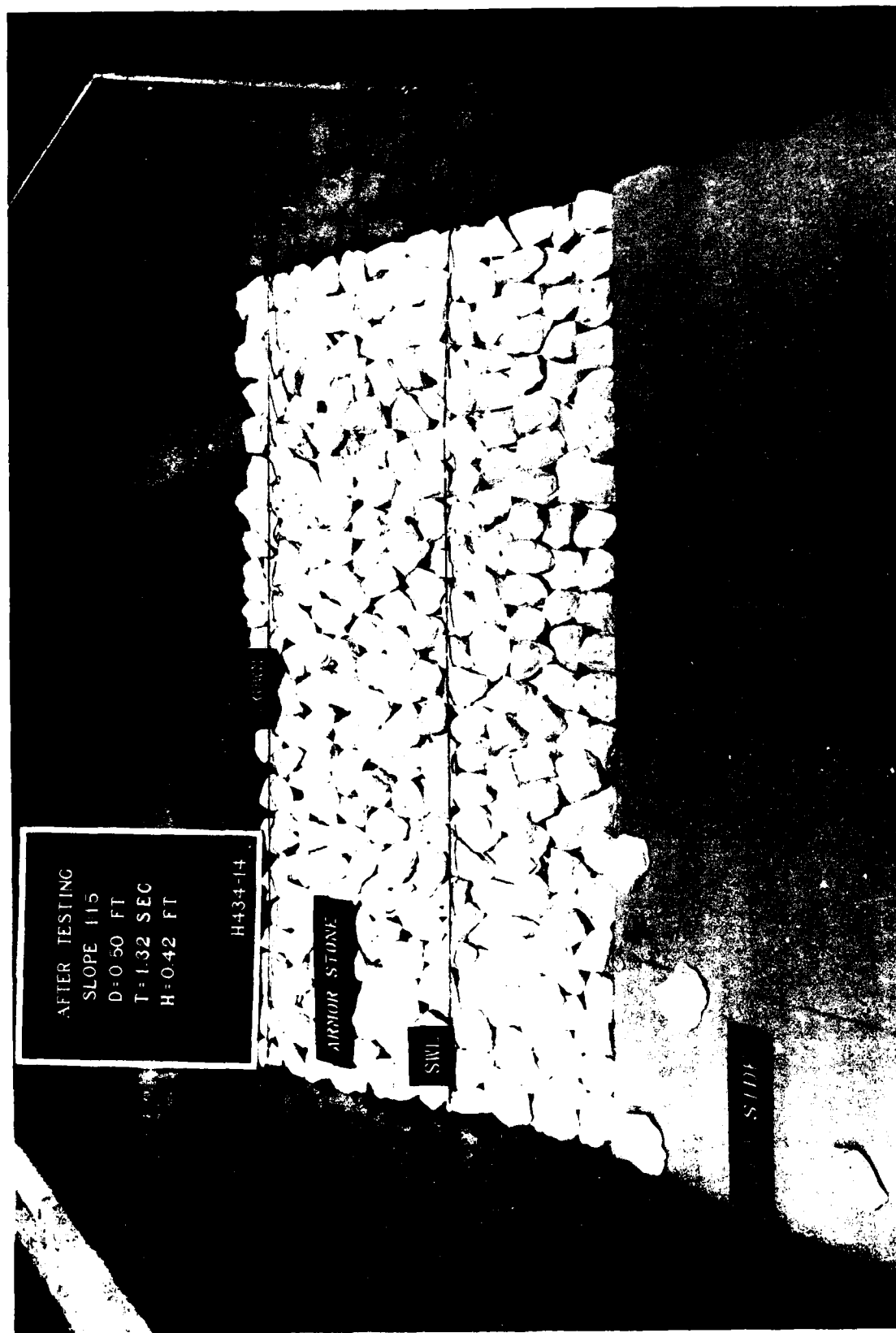


Photo 30. Sea-side view after attack of 1.32-sec, 0.42-ft waves;  $d = 0.50$  ft;  $W_a = 0.71$  lb; 1V-on-1.5H structure slope; stone armor

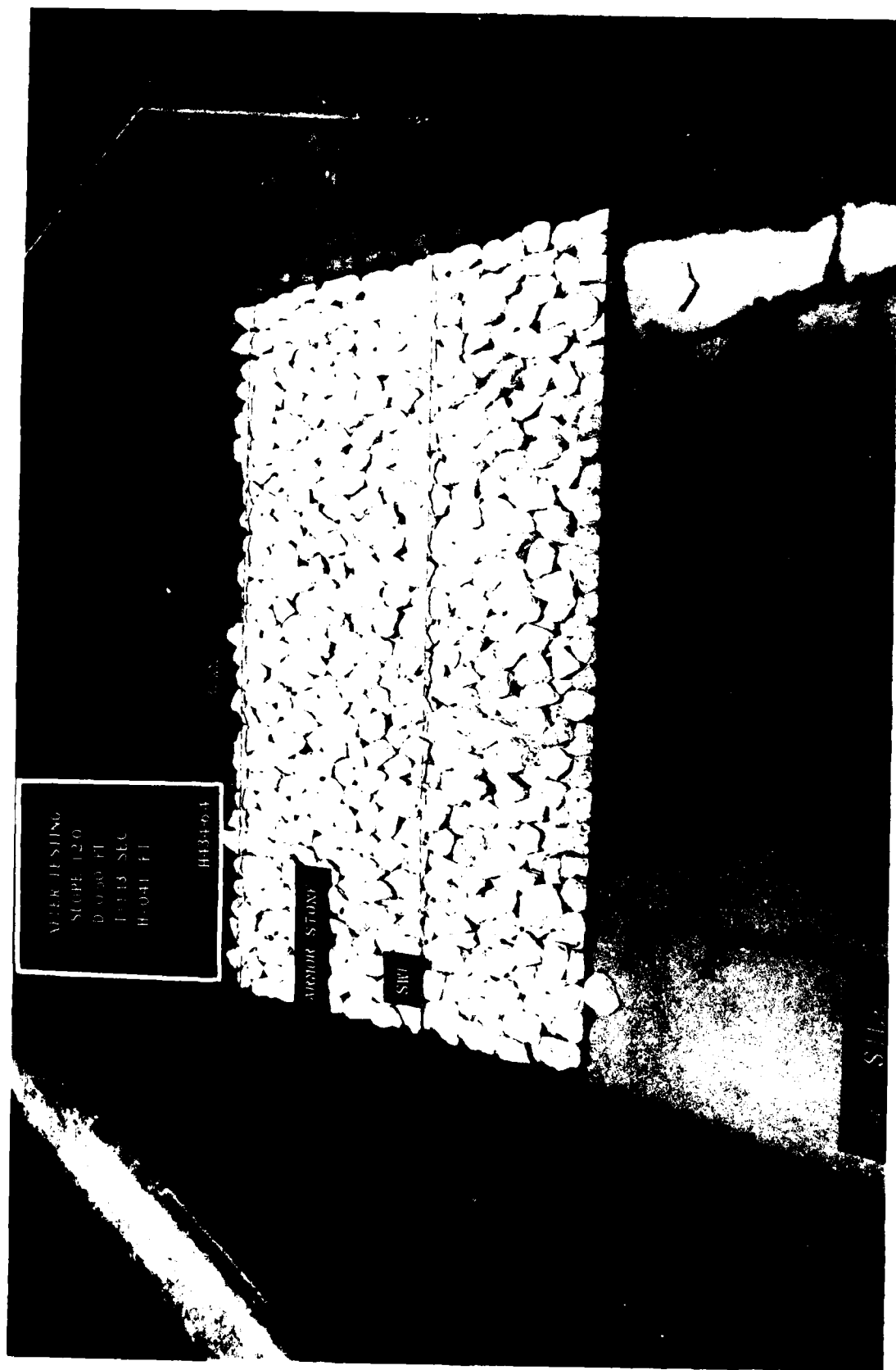


Photo 31. Sea-side view after attack of 1.13-sec, 0.41-ft waves;  $d = 0.50$  ft;  $W_a = 0.38$  lb;  
IV-on-2H structure slope; stone armor



AFTER TESTING  
SLOPE 1:2.0  
D=0.95 FT  
T=1.18 SEC  
H=0.38 FT

H434-68

ARMOR STONE

SWL

SEA SIDE

Photo 32. Sea-side view after attack of 1.18-sec, 0.38-ft waves;  $d = 0.55$  ft;  $W_a = 0.38$  lb; 1V-on-2H structure slope; stone armor



Photo 33. Sea-side view after attack of 1.09-sec, 0.40-ft waves;  $d = 0.60$  ft;  $W_a = 0.38$  lb;  
 1V-on-2H structure slope; stone armor

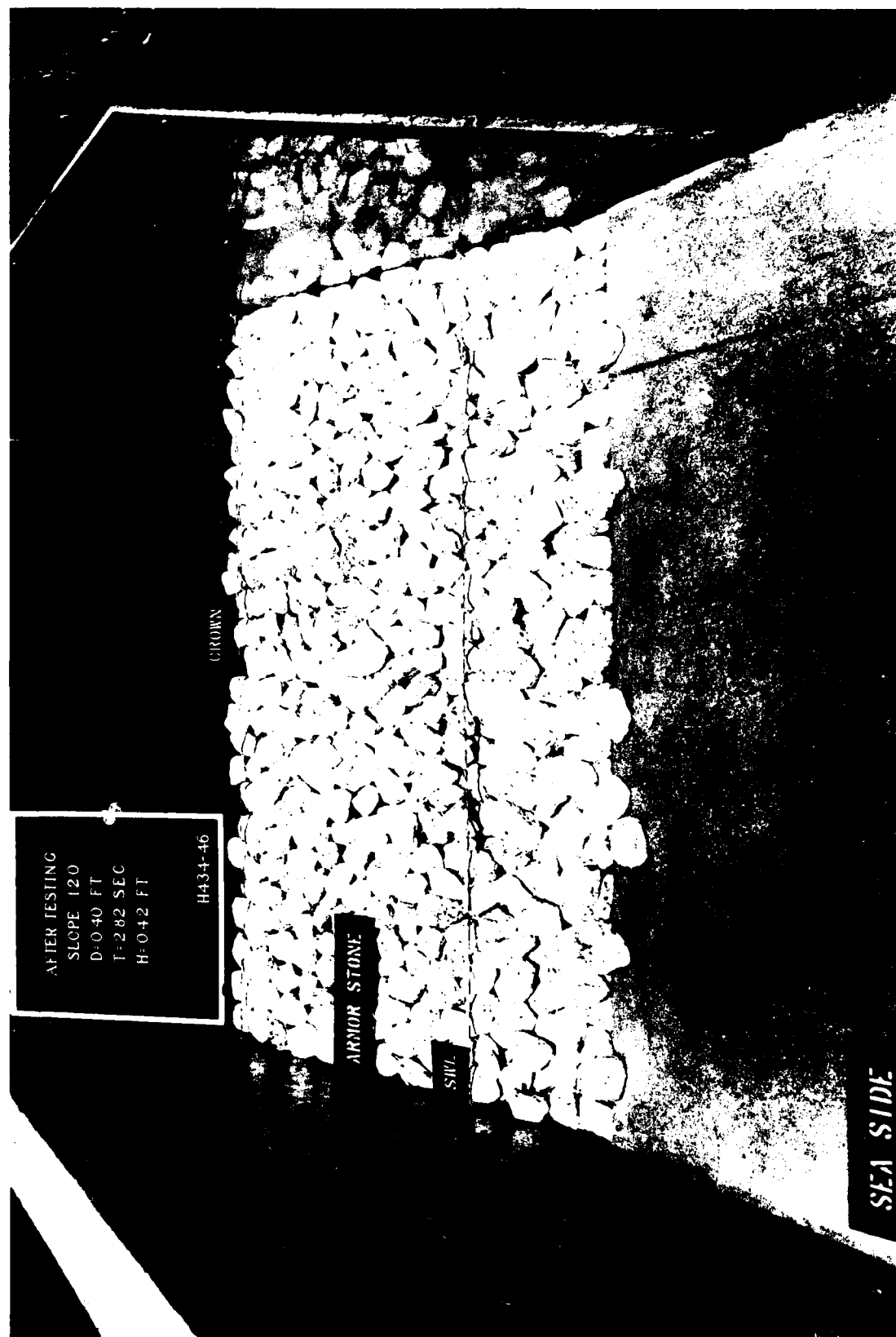


Photo 34. Sea-side view after attack of 2.82-sec, 0.42-ft waves;  $d = 0.40$  ft;  $W_a = 0.55$  lb;  
1V-on-2H structure slope; stone armor

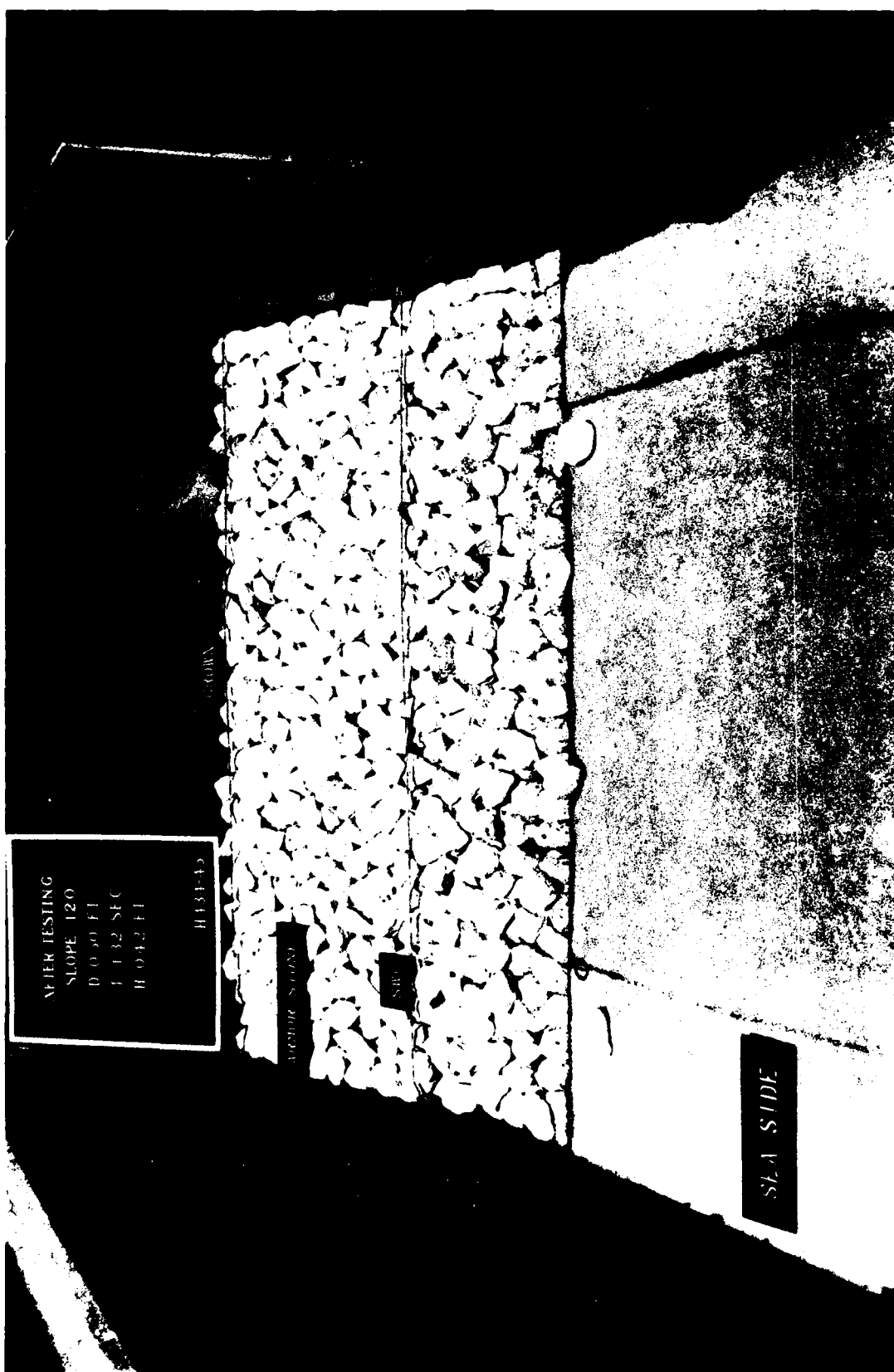


Photo 35. Sea-side view after attack of 1.32-sec, 0.42-ft waves;  $d = 0.50$  ft;  $w_a = 0.55$  lb;  
 1V-on-2H structure slope; stone armor

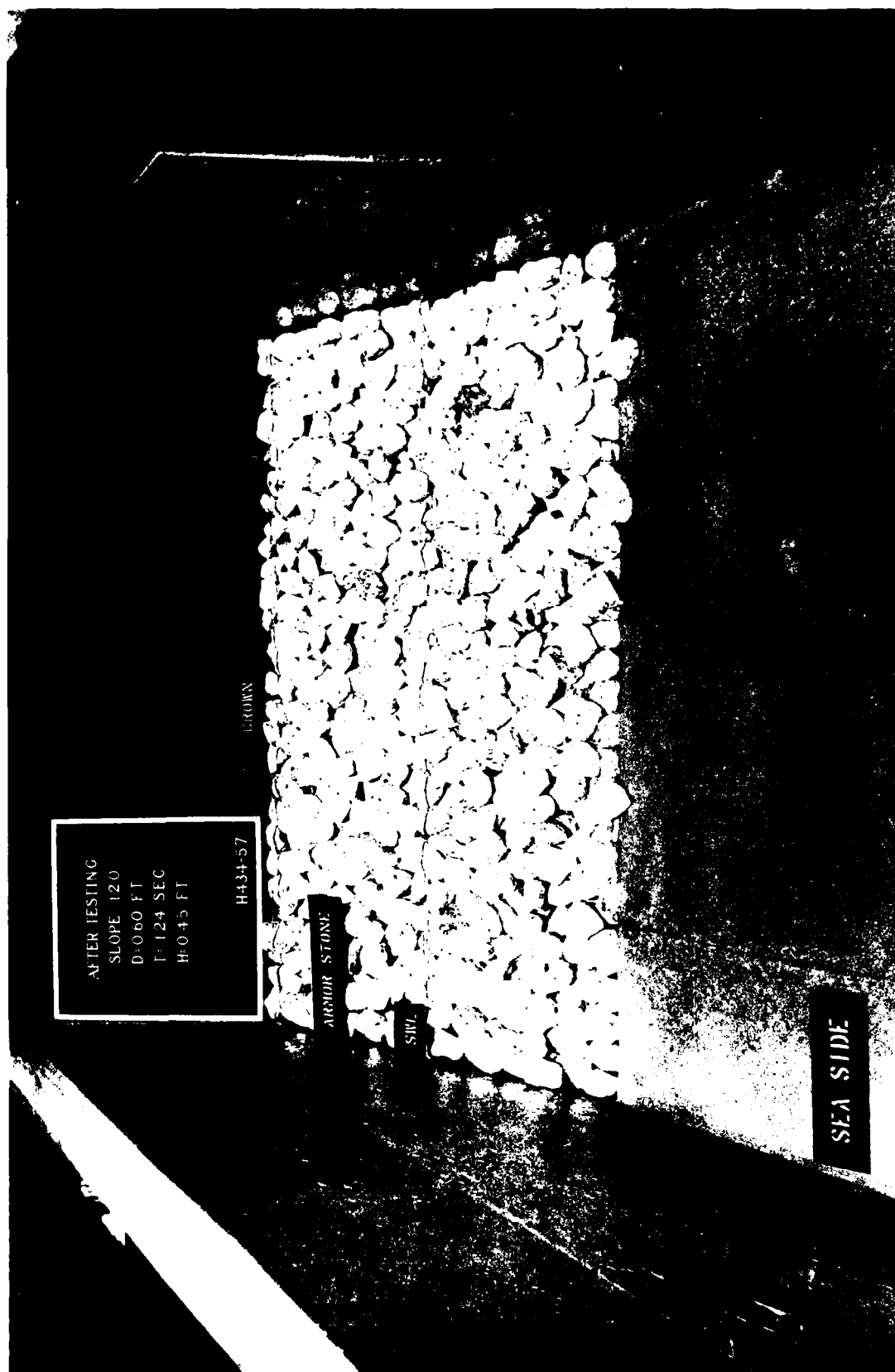


Photo 36. Sea-side view after attack of 1.24-sec, 0.45-ft waves;  $d = 0.60$  ft;  $W_a = 0.55$  lb; 1V-on-2H structure slope; stone armor

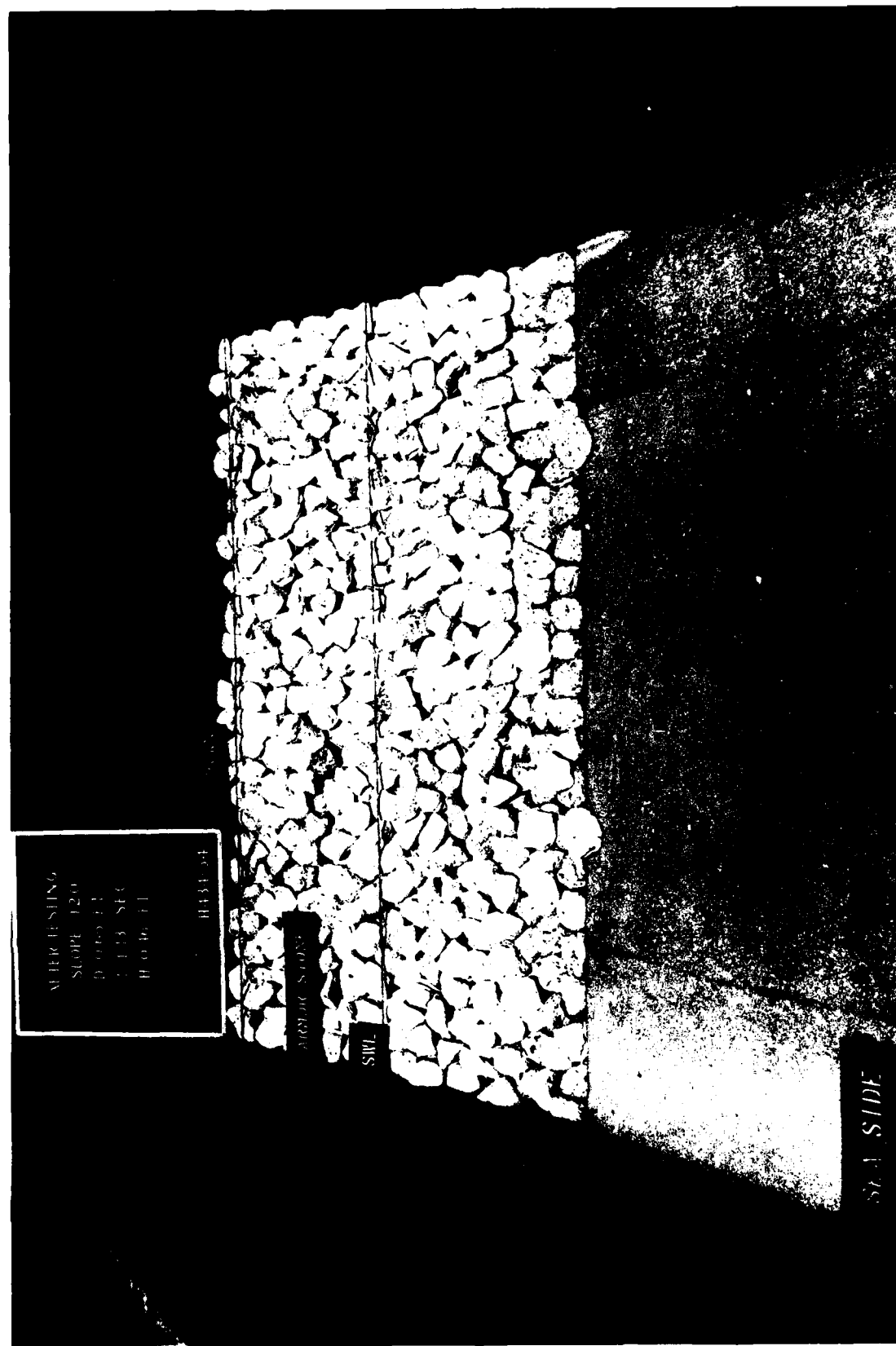


Photo 37. Sea-side view after attack of 1.13-sec, 0.46-ft waves;  $d = 0.65$  ft;  $W_a = 0.55$  lb;  
1V-on-2H structure slope; stone armor



Photo 38. Sea-side view after attack of 2.02-sec, 0.46-ft waves;  $d = 0.45$  ft;  $W_a = 0.71$  lb;  
 1V-on-2H structure slope; stone armor

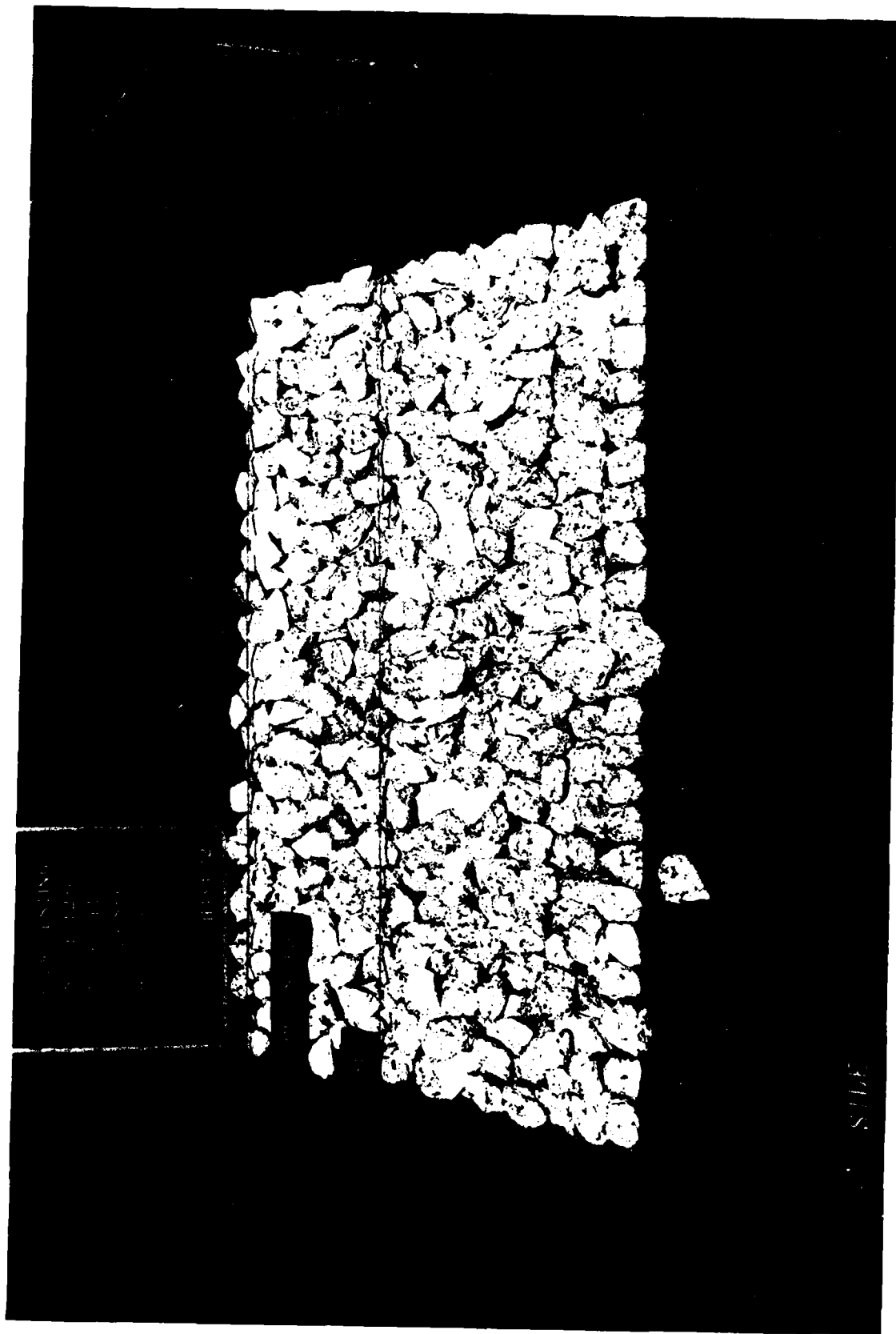


Photo 39. Sea-side view after attack of 1.29-sec, 0.51-ft waves;  $d = 0.65$  ft;  $W_a = 0.71$  lb;  
IV-on-2H structure slope; stone armor

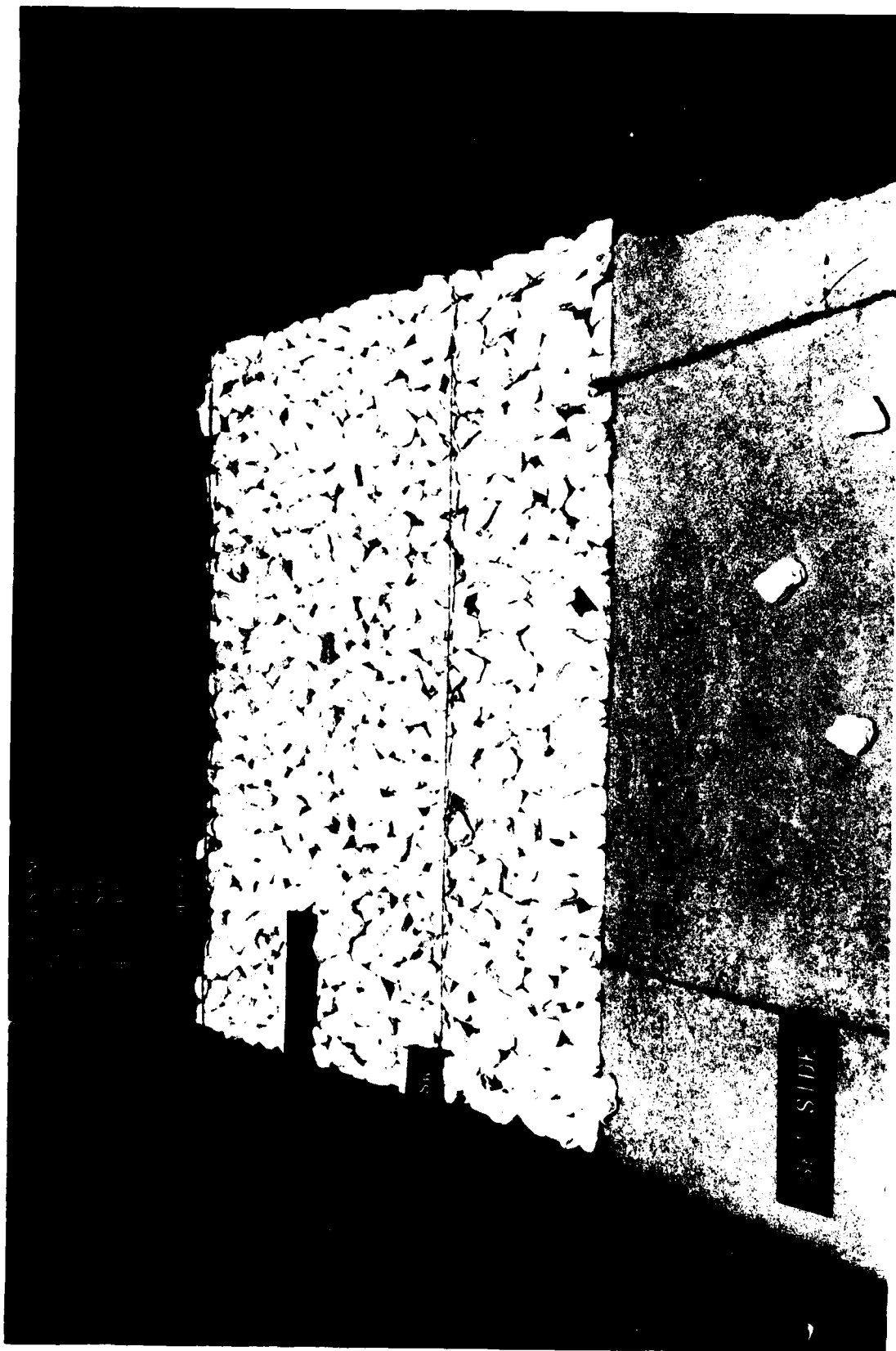


Photo 40. Sea-side view after attack of 2.82-sec, 0.42-ft waves;  $d = 0.40$  ft;  $W_a = 0.38$  lb;  
IV-on-3H structure slope; stone armor

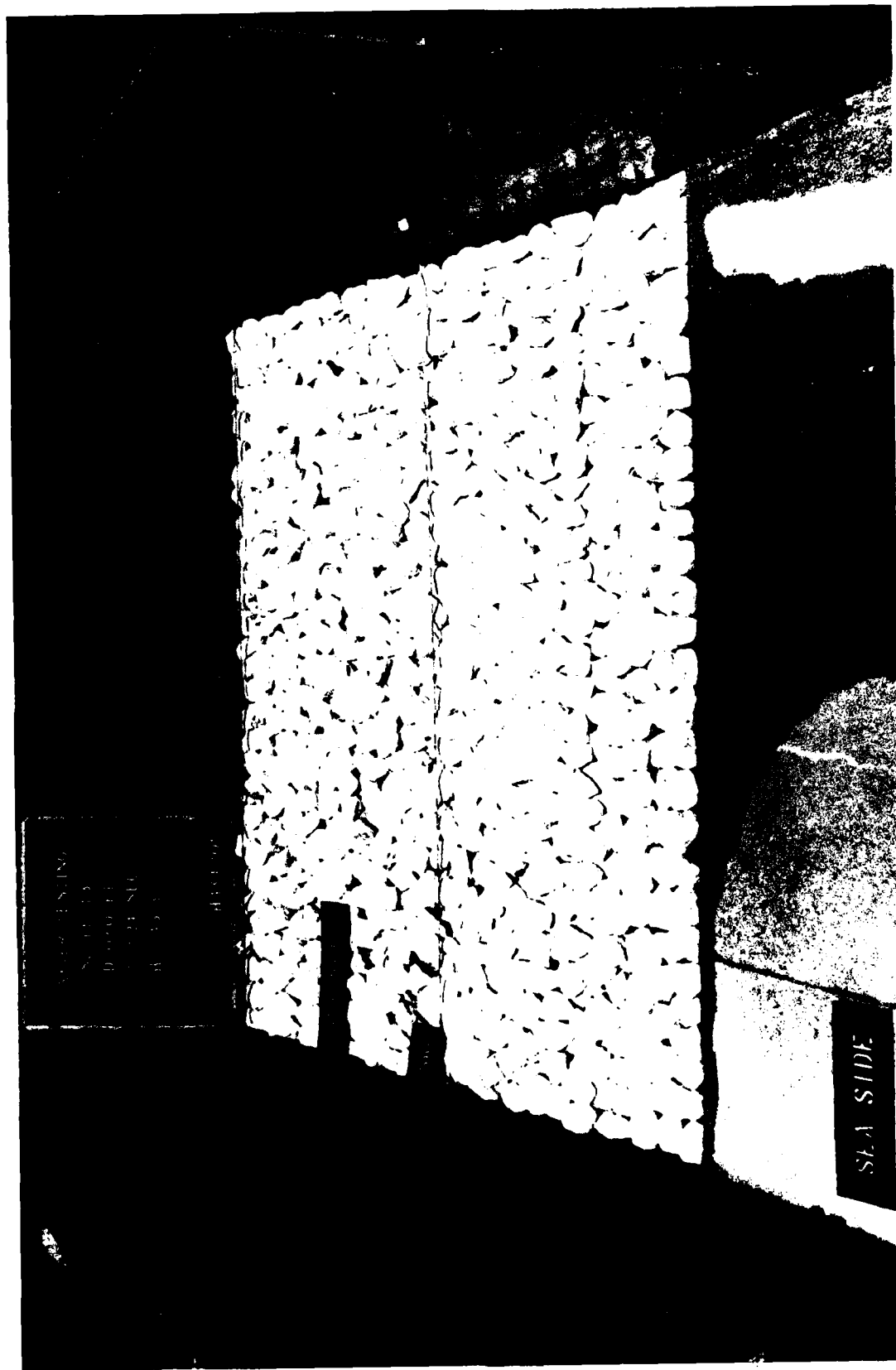


Photo 41. Sea-side view after attack of 1.24-sec, 0.45-ft waves;  $d = 0.60$  ft;  $W_a = 0.38$  lb;  
1V-on-3H structure slope; stone armor

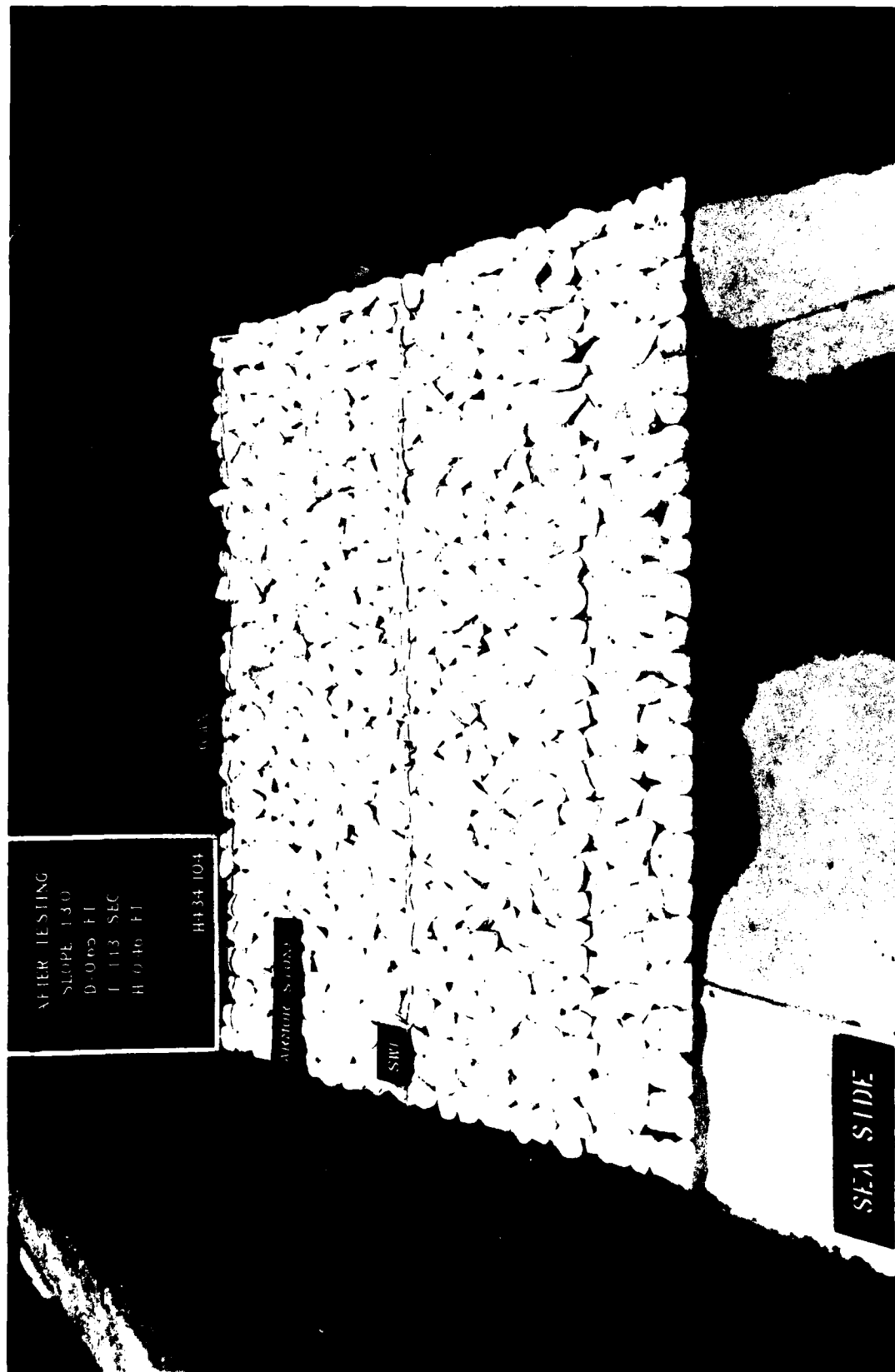


Photo 42. Sea-side view after attack of 1.13-sec, 0.46-ft waves;  $d = 0.65$  ft;  $W_a = 0.38$  lb; IV-on-3H structure slope; stone armor

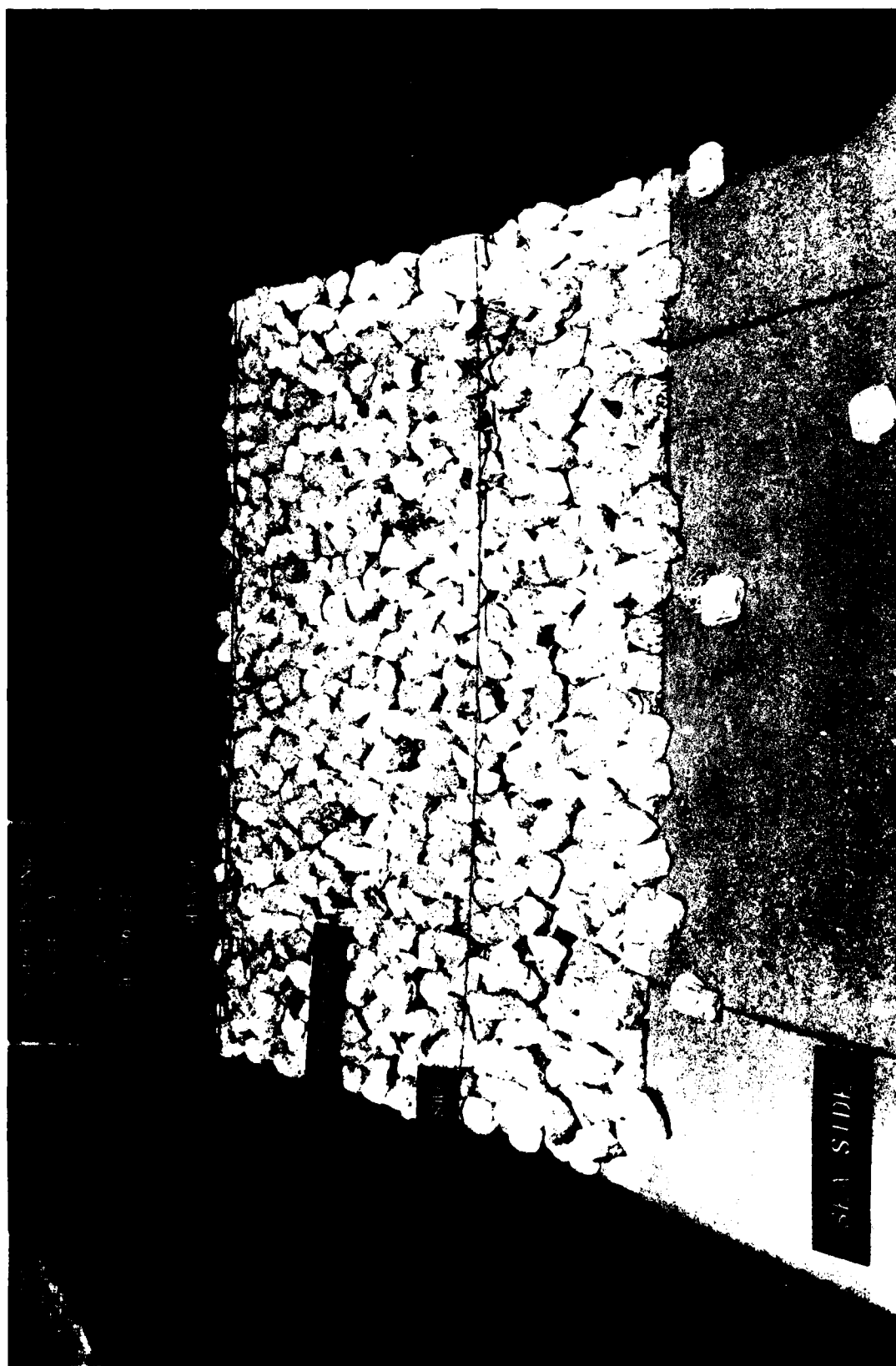


Photo 43. Sea-side view after attack of 2.02-sec, 0.46-ft waves;  $d = 0.45$  ft;  $W_a = 0.55$  lb;  
IV-on-3H structure slope; stone armor

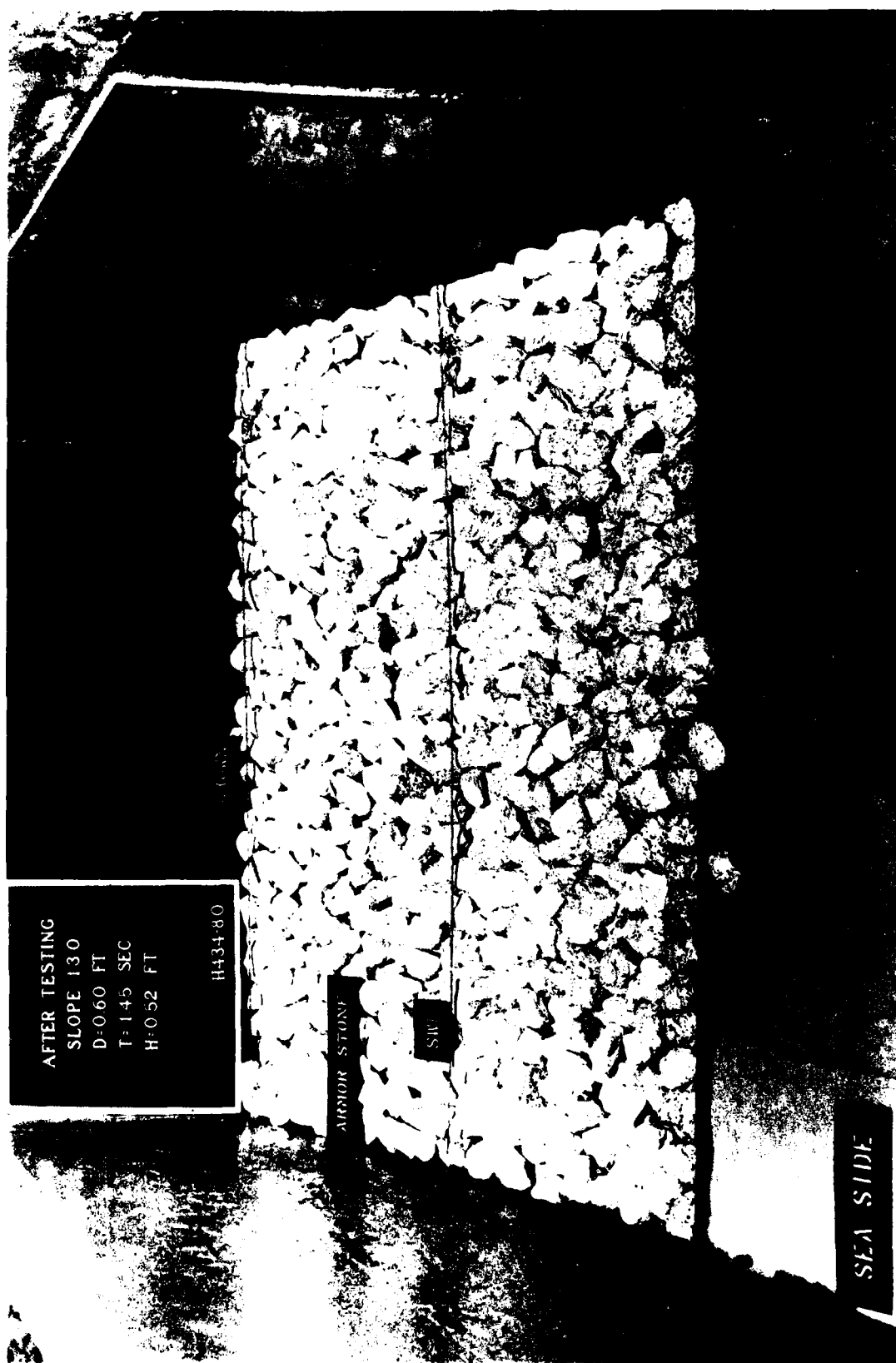


Photo 44. Sea-side view after attack of 1.45-sec, 0.52-ft waves;  $d = 0.60$  ft;  $W_a = 0.55$  lb;  
IV-on-3H structure slope; stone armor

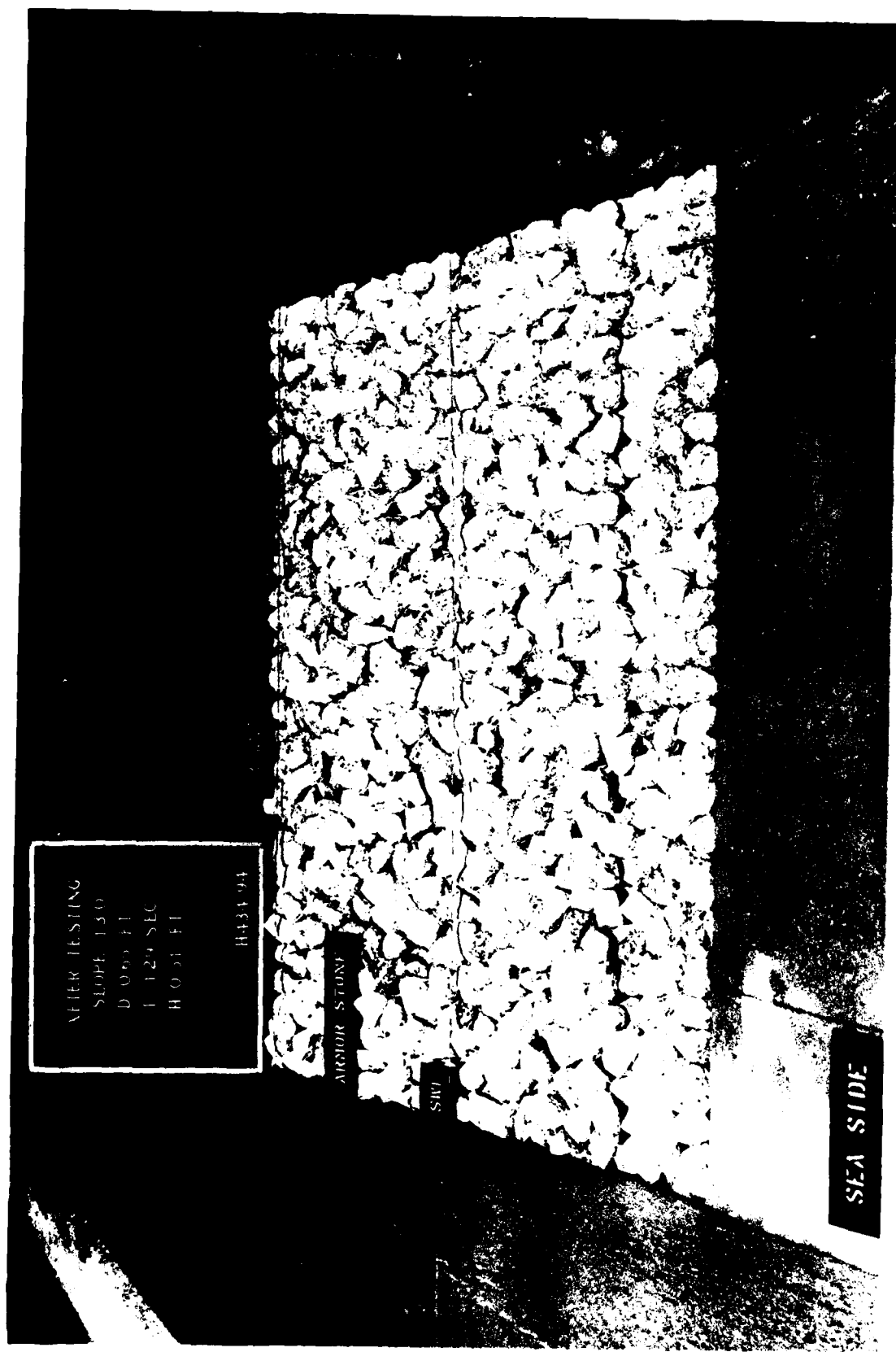


Photo 45. Sea-side view after attack of 1.29-sec, 0.51-ft waves;  $d = 0.65$  ft;  $W_a = 0.55$  lb; IV-on-3H structure slope; stone armor

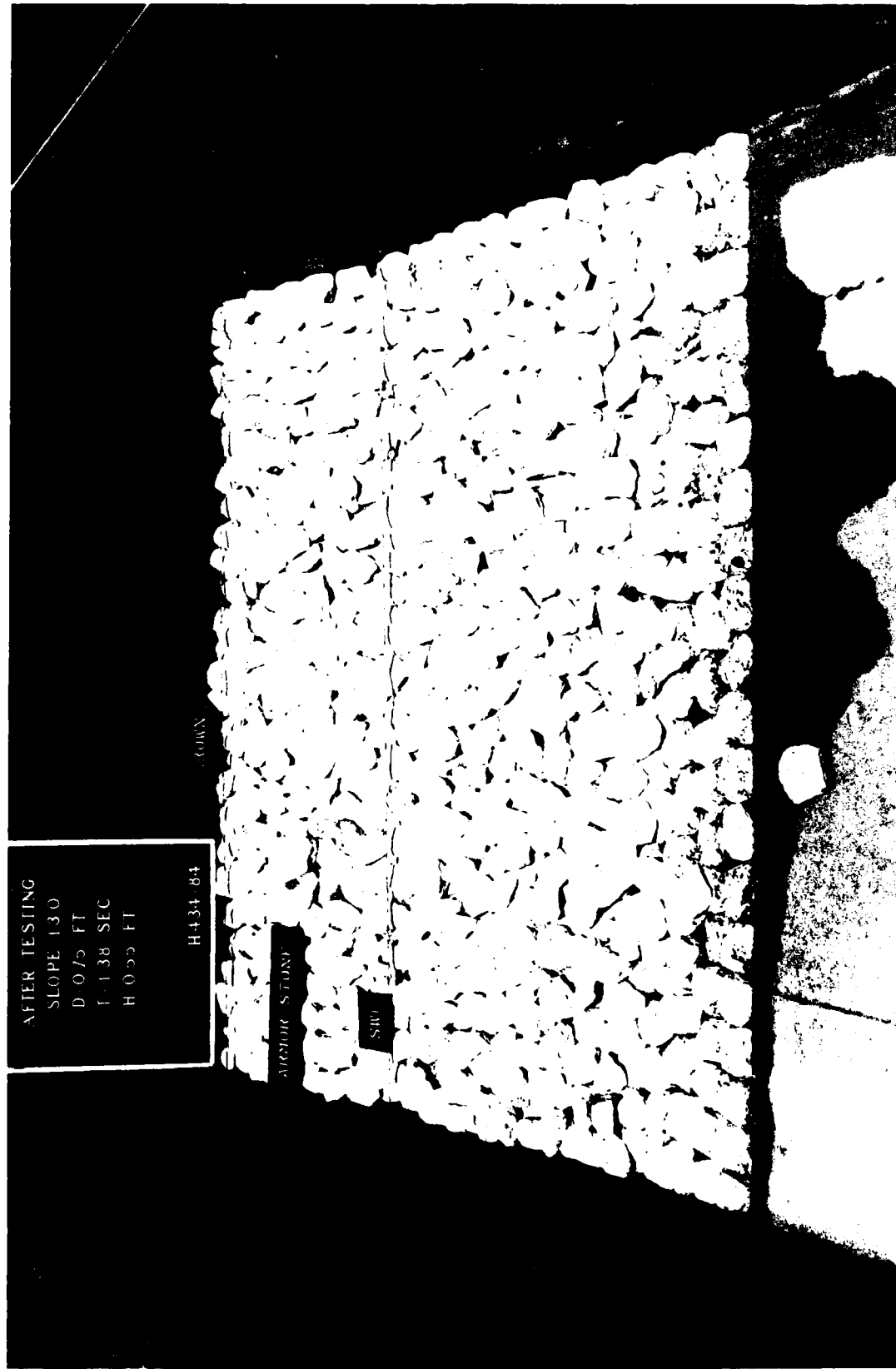


Photo 46. Sea-side view after attack of 1.38-sec, 0.55-ft waves;  $d = 0.75$  ft;  $W_a = 0.55$  lb;  
1V-on-3H structure slope; stone armor

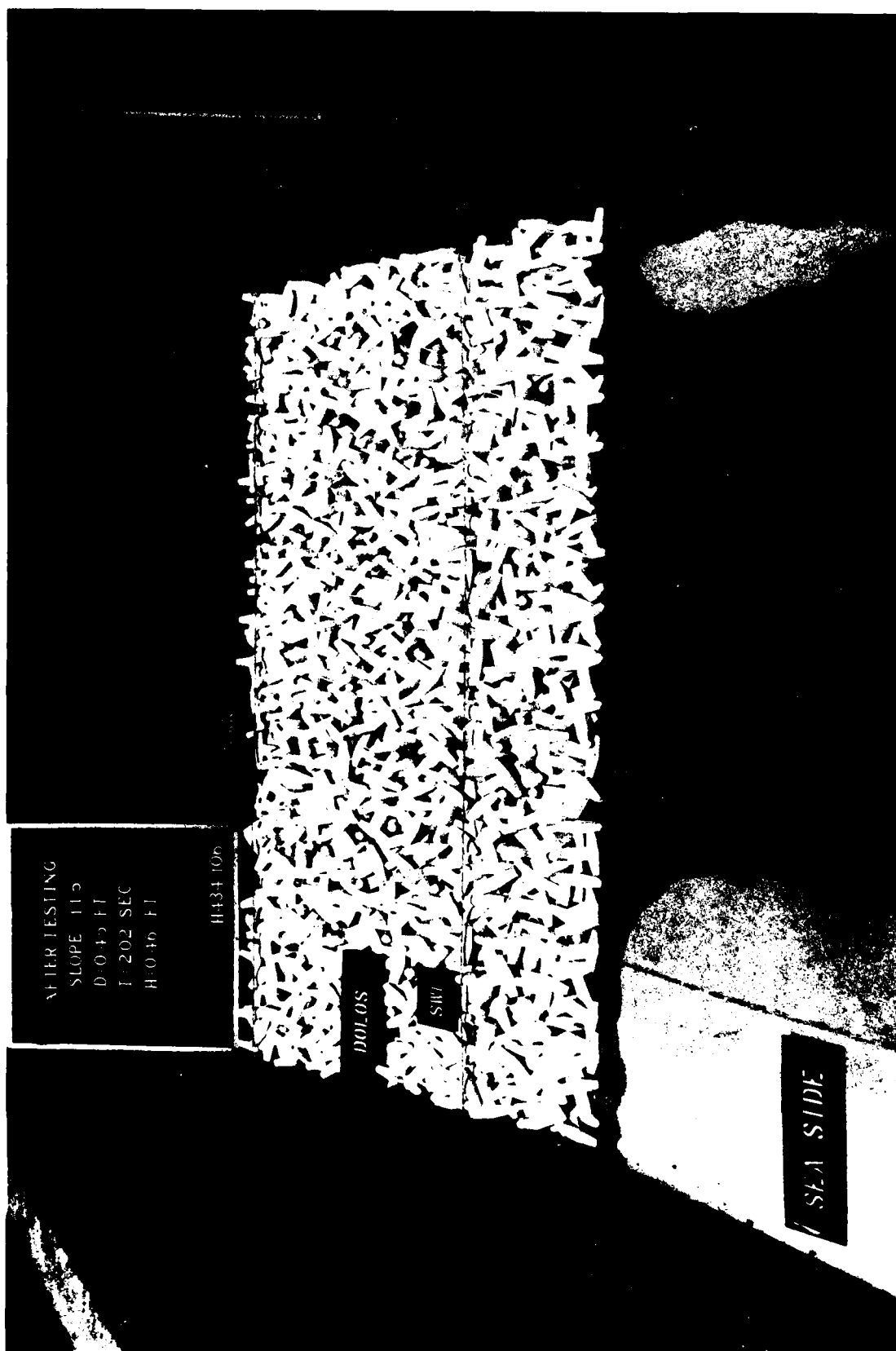


Photo 47. Sea-side view after attack of 2.02-sec, 0.46-ft waves;  $d = 0.45$  ft;  $W_a = 0.276$  lb;  
IV-on-1.5H structure slope; dolos armor

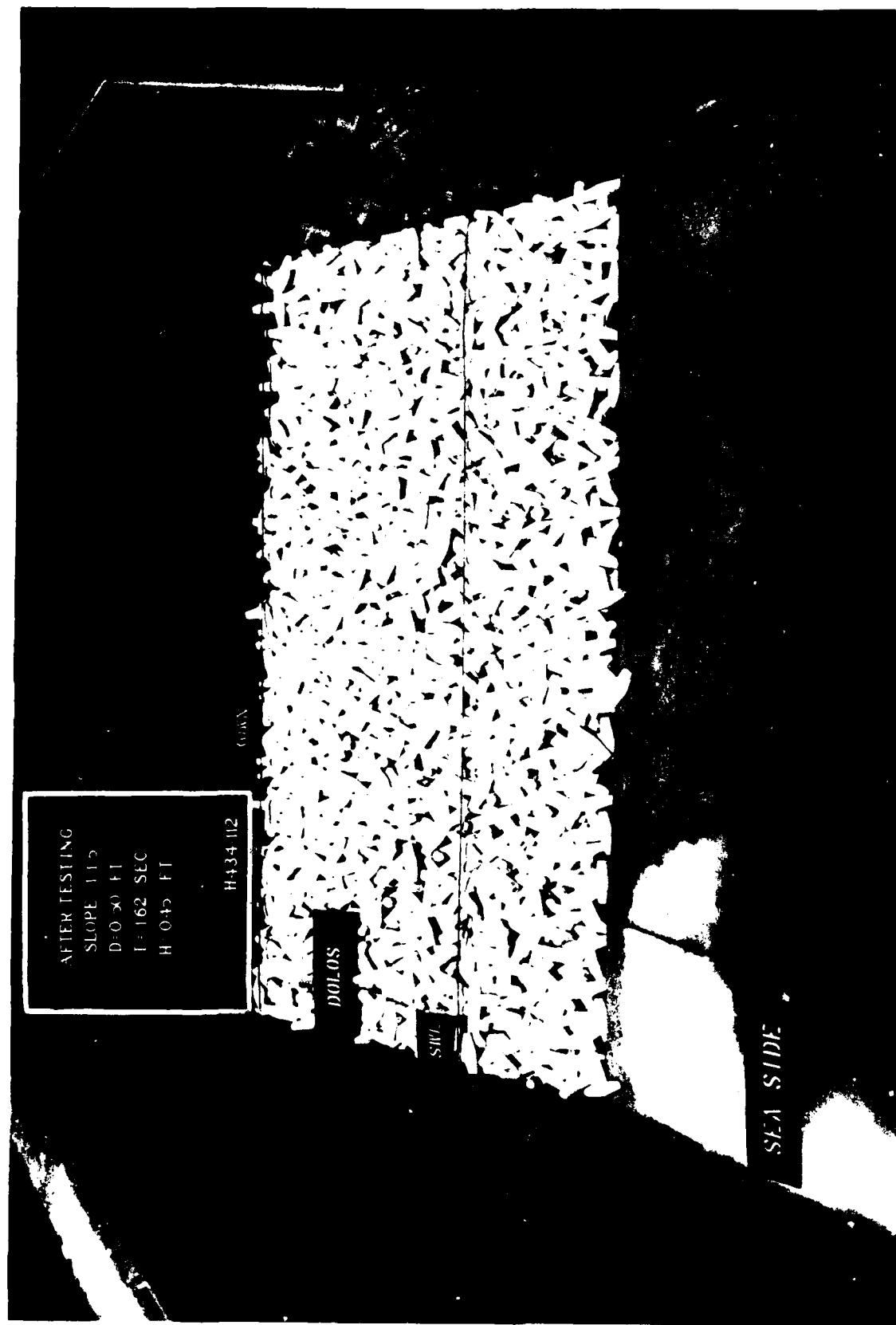


Photo 48. Sea-side view after attack of 1.62-sec, 0.45-ft waves;  $d = 0.50$  ft;  $W_a = 0.276$  lb;  
IV-on-1.5H structure slope; dolos armor

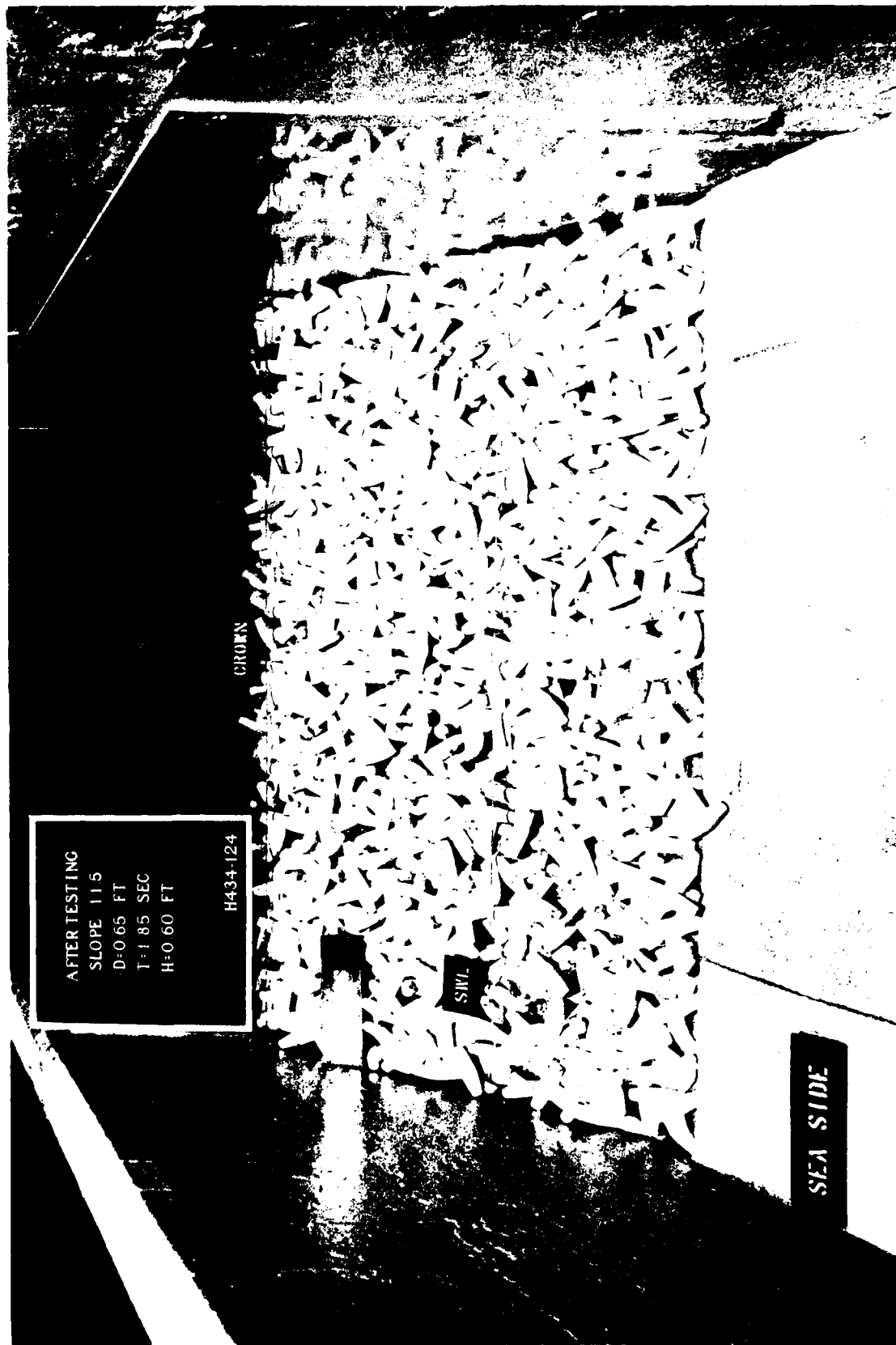


Photo 49. Sea-side view after attack of 1.85-sec, 0.60-ft waves;  $d = 0.65$  ft;  $W_a = 0.589$  lb;  
1V-on-1.5H structure slope; dolos armor



Photo 50. Sea-side view after attack of 1.73-sec, 0.71-ft waves;  $d = 0.85$  ft;  $W_a = 0.589$  lb;  
1V-on-1.5H structure slope; dolos armor

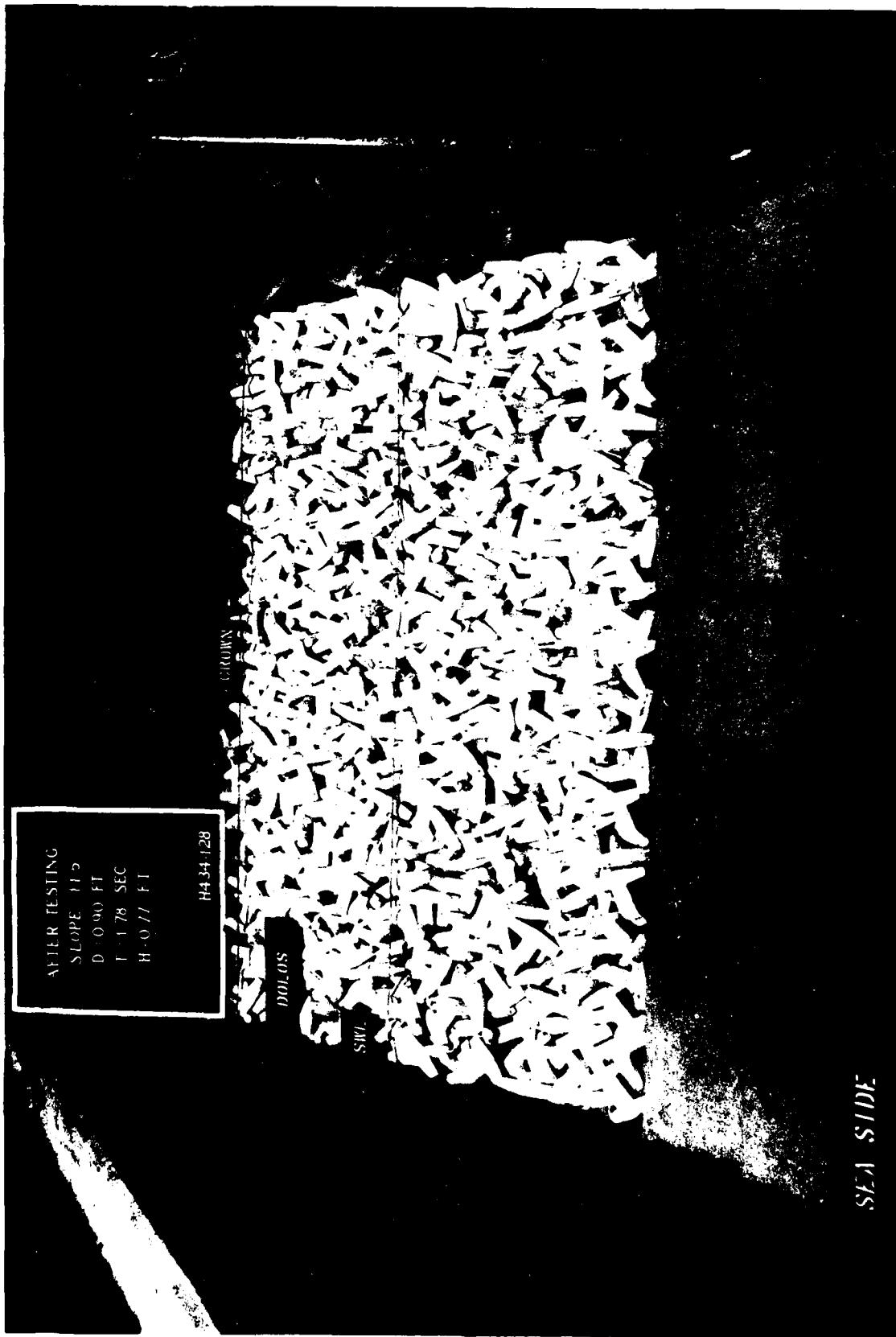


Photo 51. Sea-side view after attack of 1.78-sec, 0.77-ft waves;  $d = 0.90$  ft;  $W_a = 0.589$  lb; 1V-on-1.5H structure slope; dolos armor

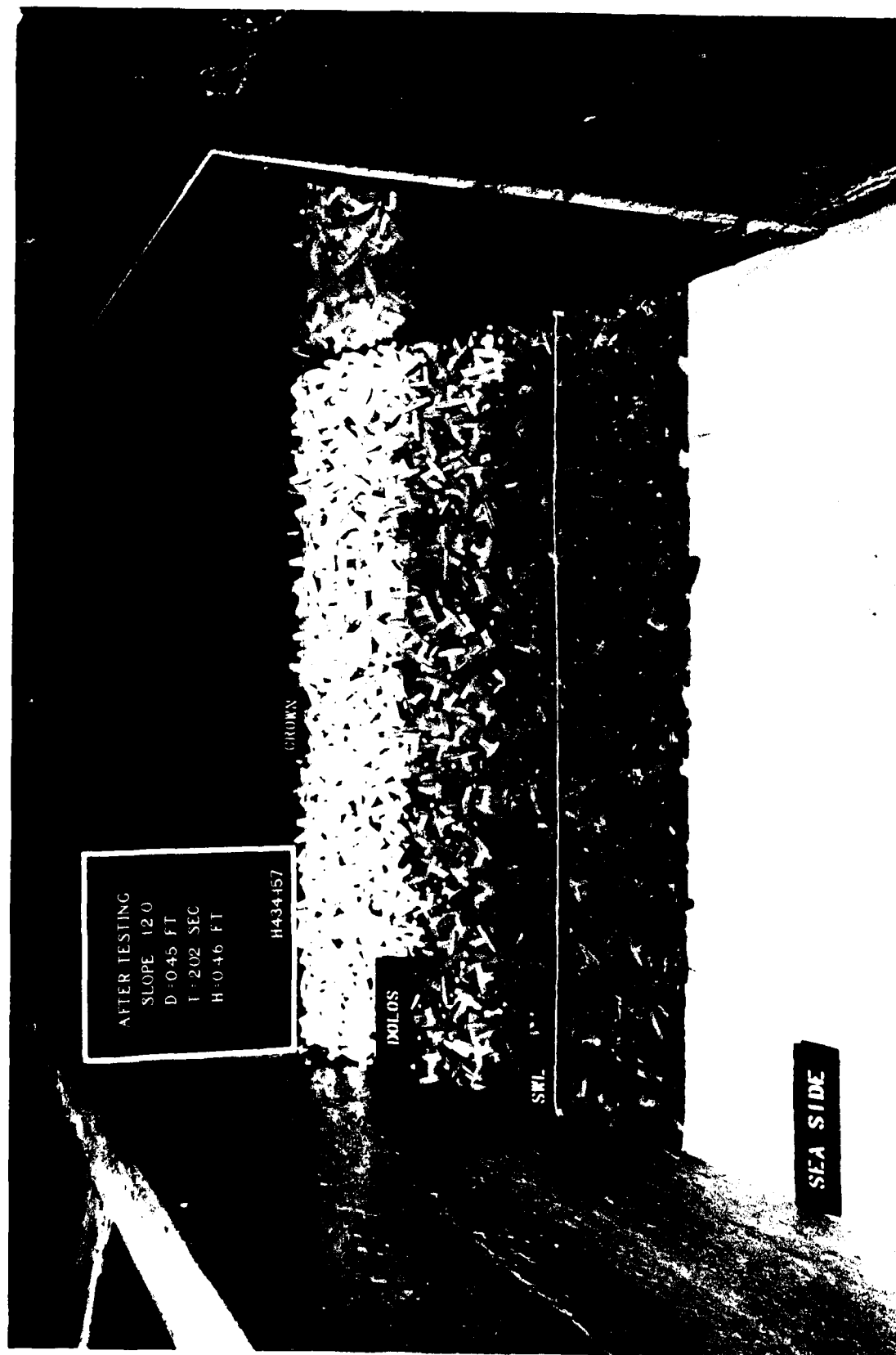


Photo 52. Sea-side view after attack of 2.02-sec, 0.46-ft waves;  $d = 0.45$  ft;  $W_a = 0.234$  lb;  
IV-on-2H structure slope; dolos armor

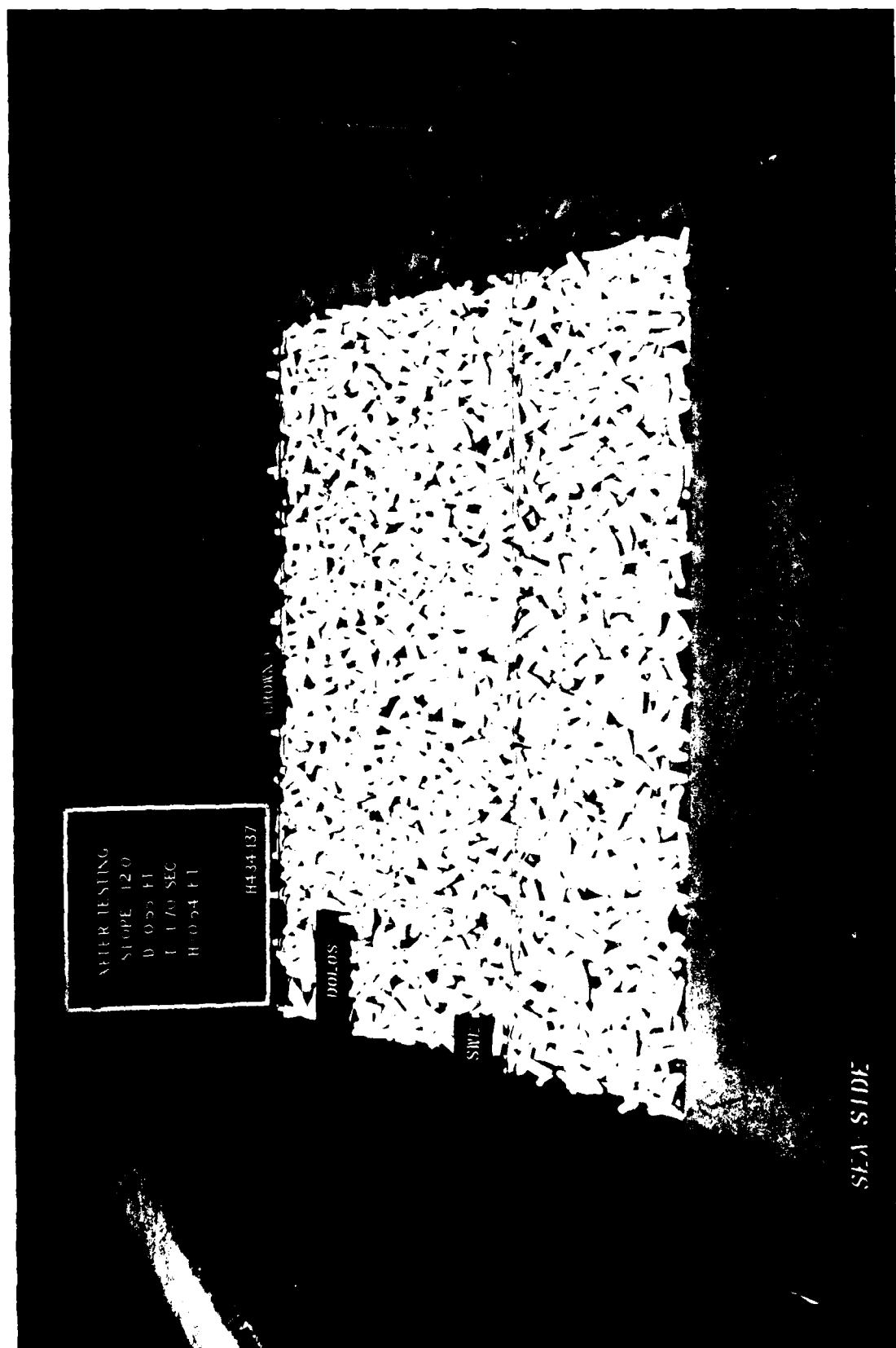


Photo 53. Sea-side view after attack of 1.70-sec, 0.54-ft waves;  $d = 0.55$  ft;  $W_a = 0.276$  lb; 1V-on-2H structure slope; dolos armor

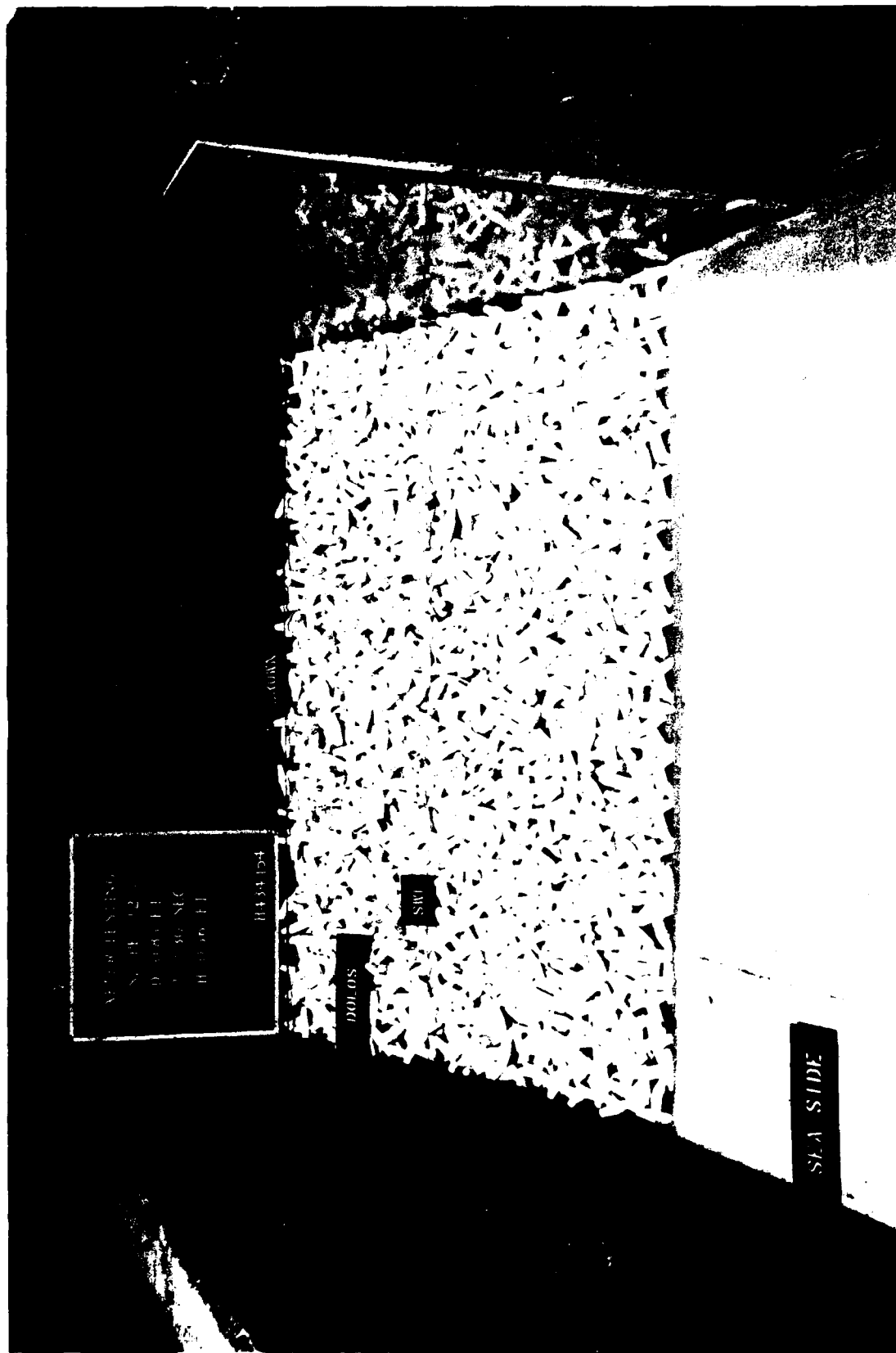


Photo 54. Sea-side view after attack of 1.30-sec, 0.56-ft waves;  $d = 0.85$  ft;  $W_a = 0.276$  lb;  
 1V-on-2H structure slope; dolos armor



Photo 55. Sea-side view after attack of 1.47-sec, 0.63-ft waves;  $d = 0.85$  ft;  $W_a = 0.276$  lb;  
IV-on-2H structure slope; dolos armor

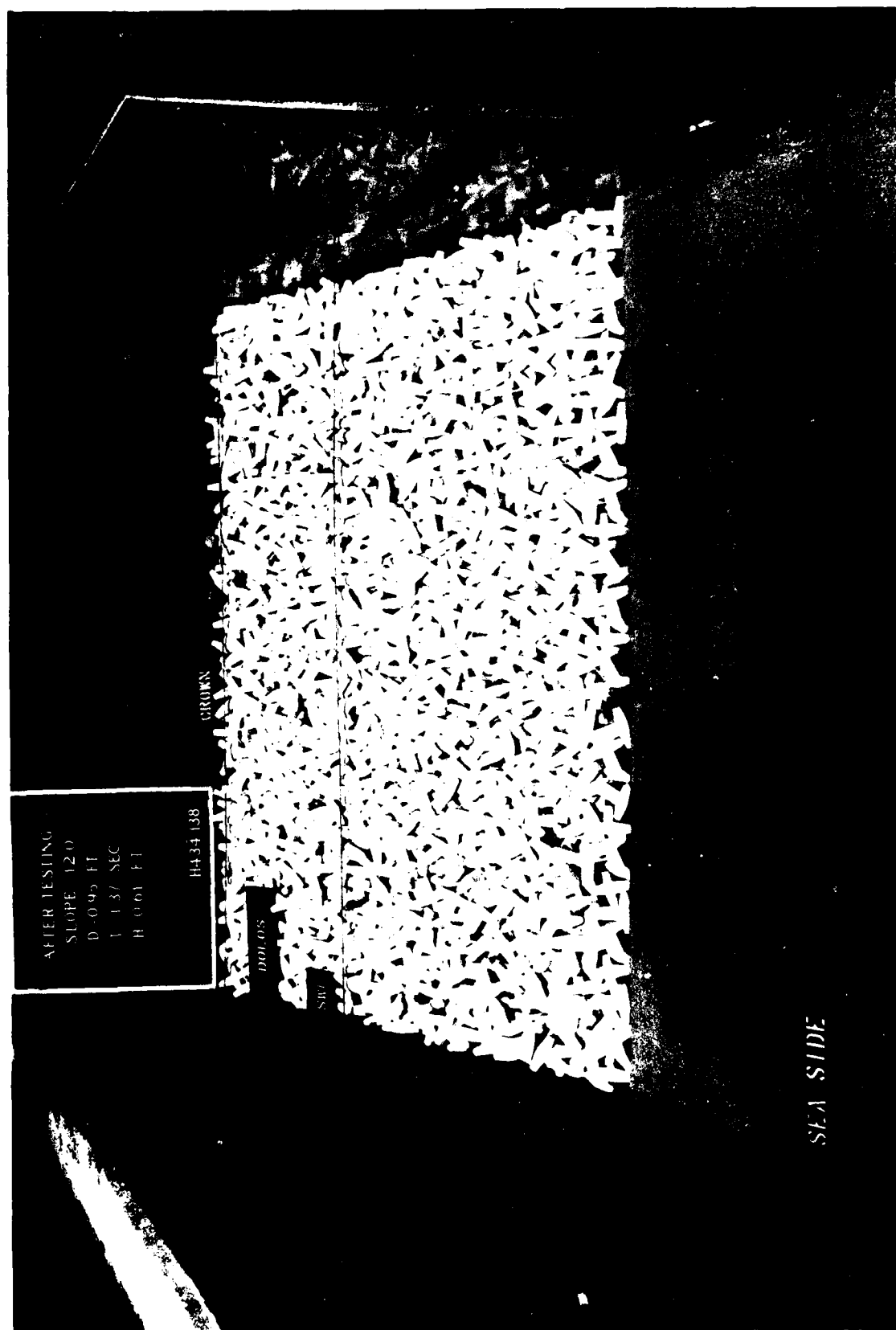


Photo 56. Sea-side view after attack of 1.37-sec, 0.61-ft waves;  $d = 0.95$  ft;  $W_a = 0.276$  lb; IV-on-2H structure slope; dolos armor

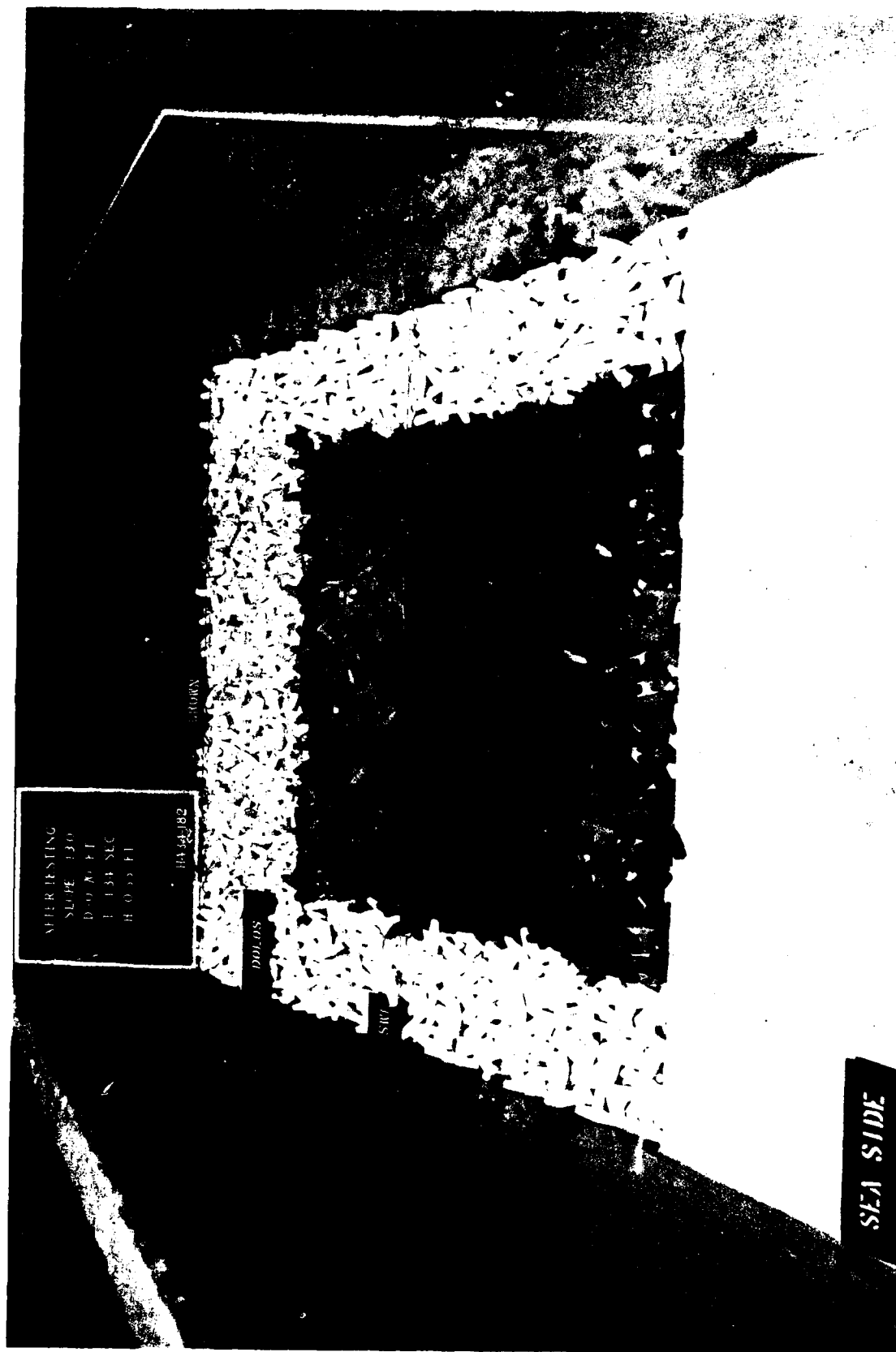


Photo 57. Sea-side view after attack of 1.34-sec, 0.55-ft waves;  $d = 0.70$  ft;  $W_a = 0.234$  lb;  
 IV-on-3H structure slope; dolos armor

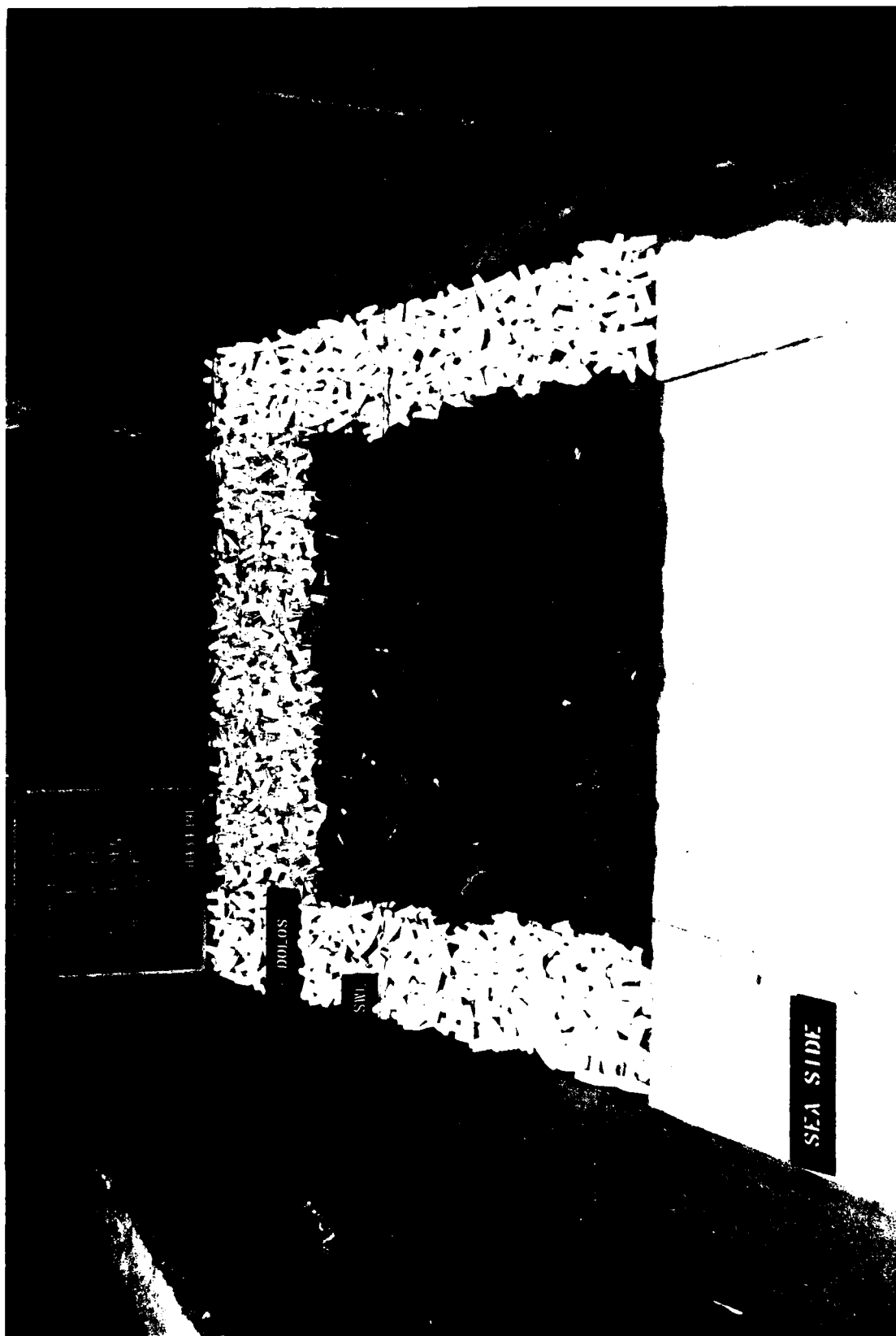


Photo 58. Sea-side view after attack of 1.43-sec, 0.55-ft waves;  $d = 0.80$  ft;  $W_a = 0.234$  lb;  
1V-on-3H structure slope; dolos armor

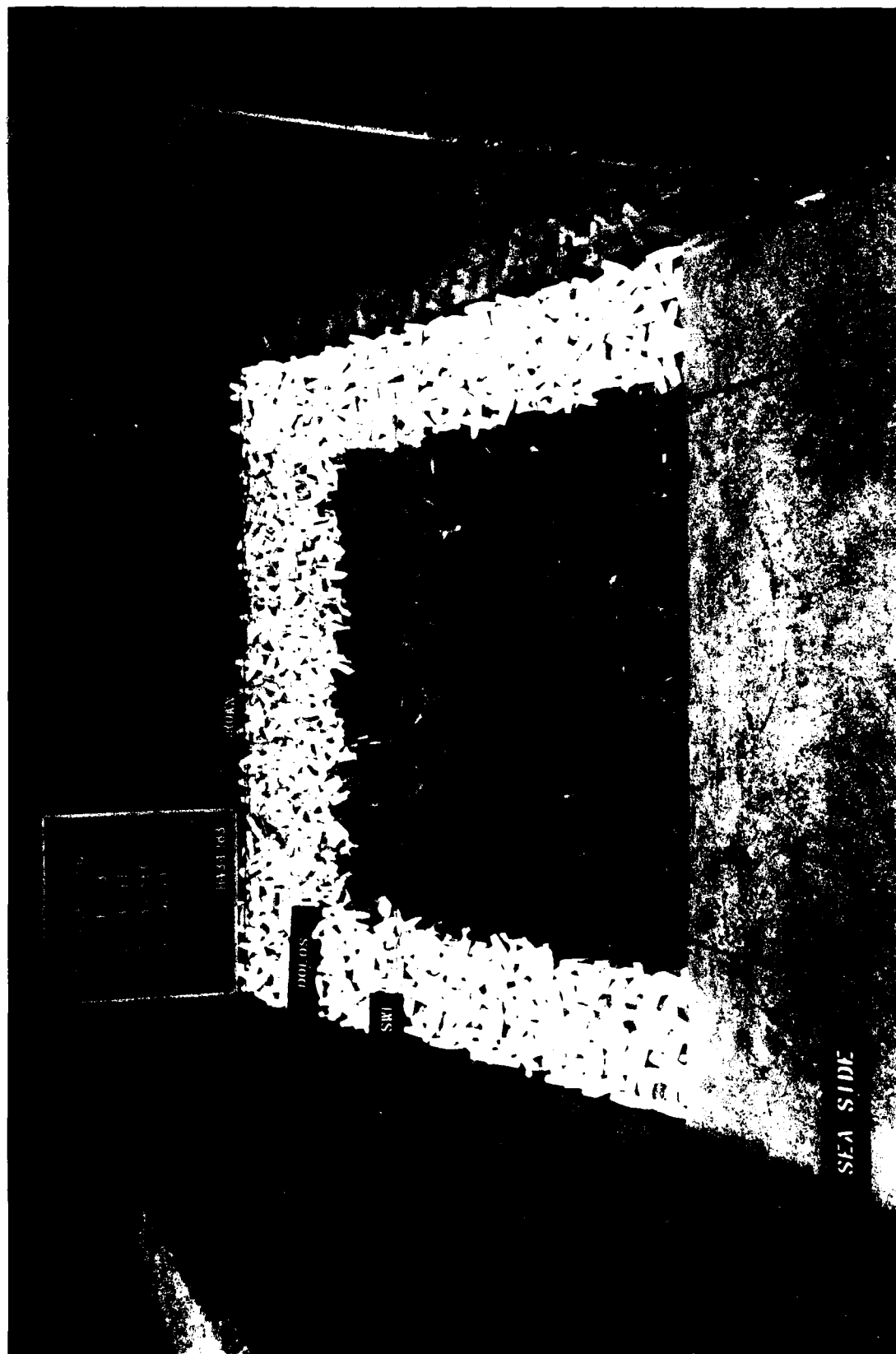


Photo 59. Sea-side view after attack of 1.30-sec, 0.56-ft waves;  $d = 0.85$  ft;  $W_a = 0.234$  lb;  
IV-on-3H structure slope; dolos armor

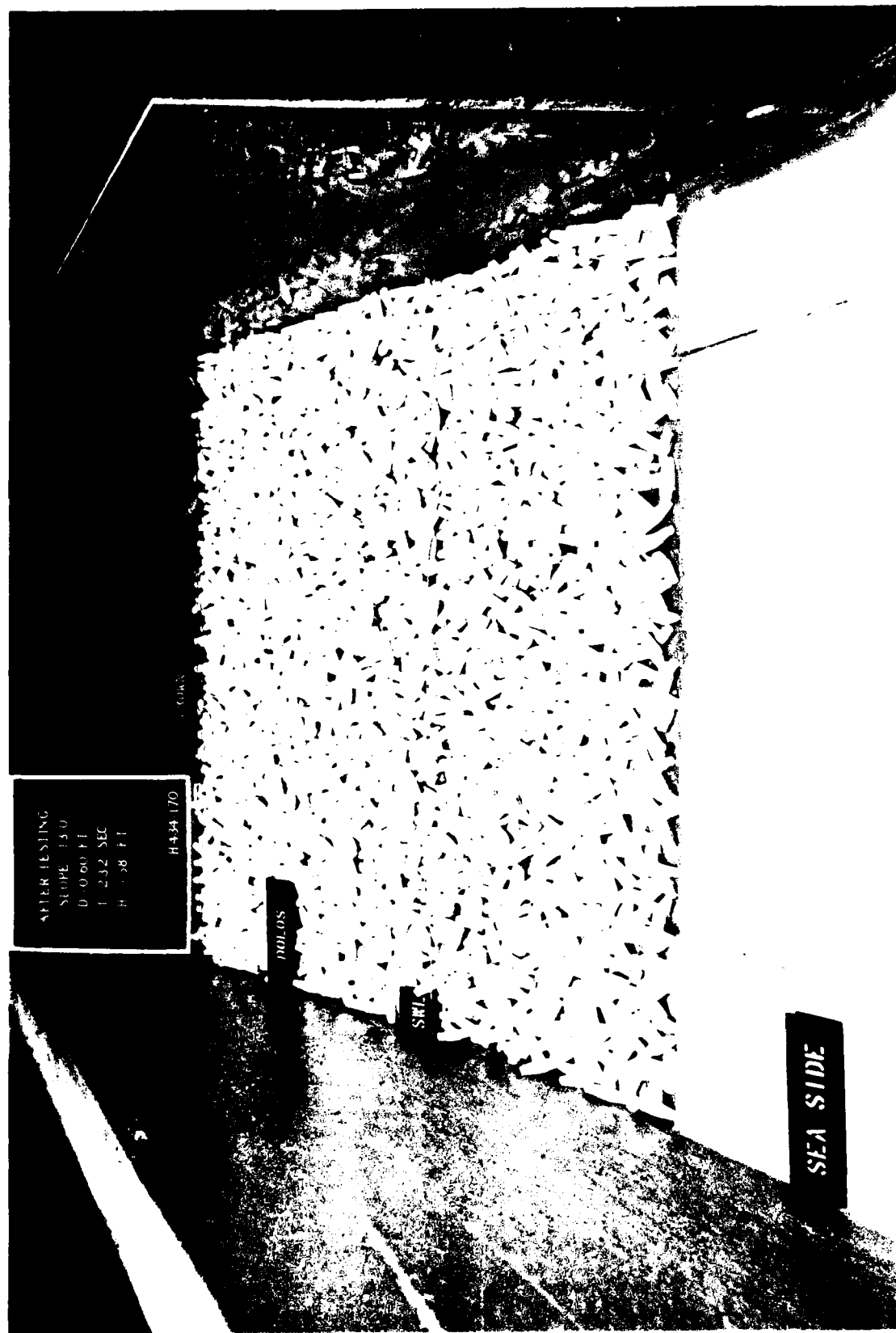


Photo 60. Sea-side view after attack of 2.32-sec, 0.58-ft waves;  $d = 0.60$  ft;  $W_a = 0.276$  lb; 1V-on-3H structure slope; dolos armor

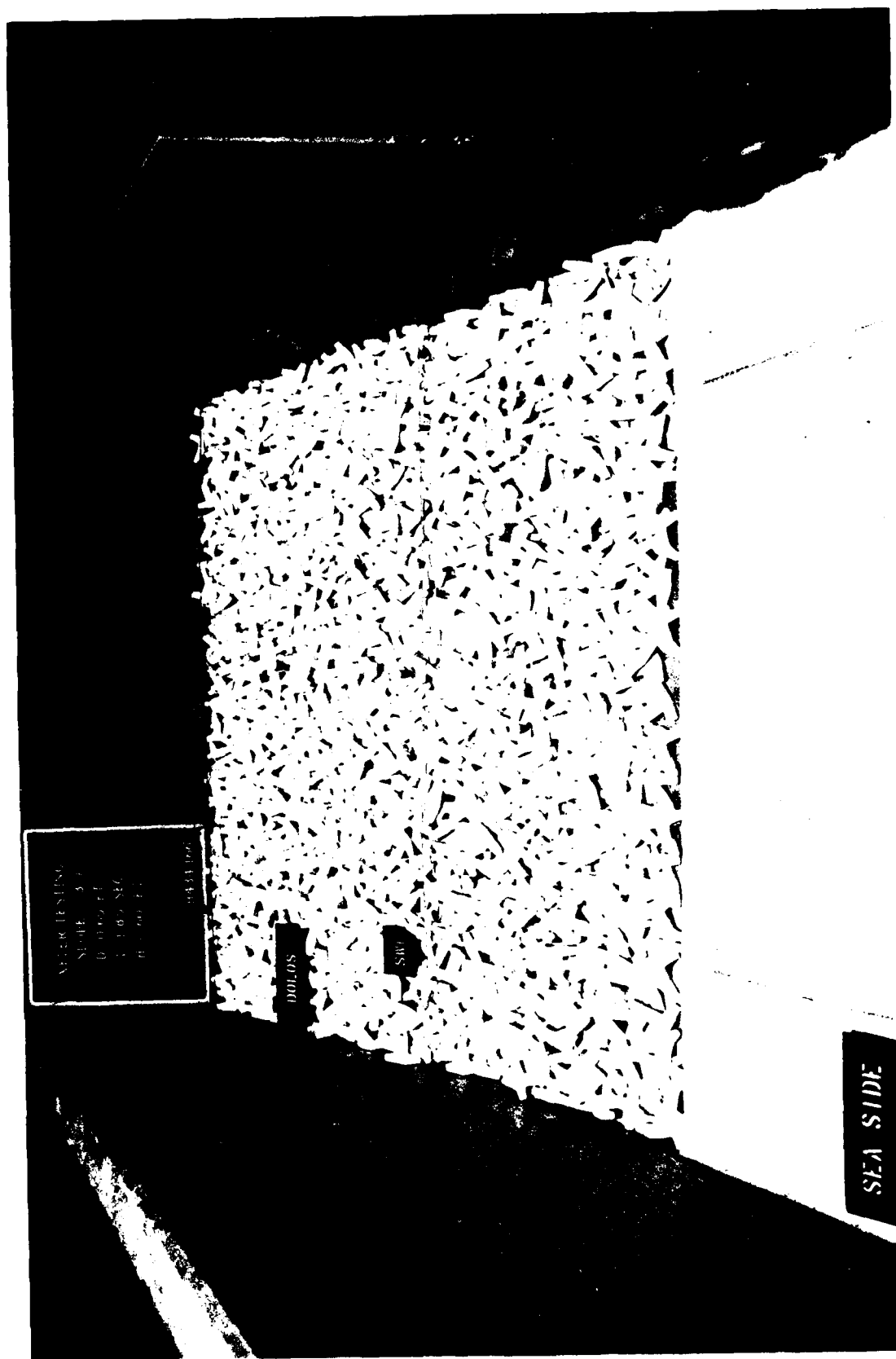


Photo 61. Sea-side view after attack of 1.85-sec, 0.60-ft waves;  $d = 0.65$  ft;  $W_a = 0.276$  lb;  
 1V-on-3H structure slope; dolos armor

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STABILITY OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND  
BREAKWATER TRUNKS SUBJ. (U) COASTAL ENGINEERING  
RESEARCH CENTER VICKSBURG MS R D CARVER DEC 83  
CERC-TR-83-5

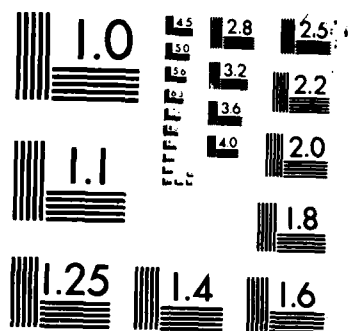
2/2

UNCLASSIFIED

F/G 13/2

NL





MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS 1963-A

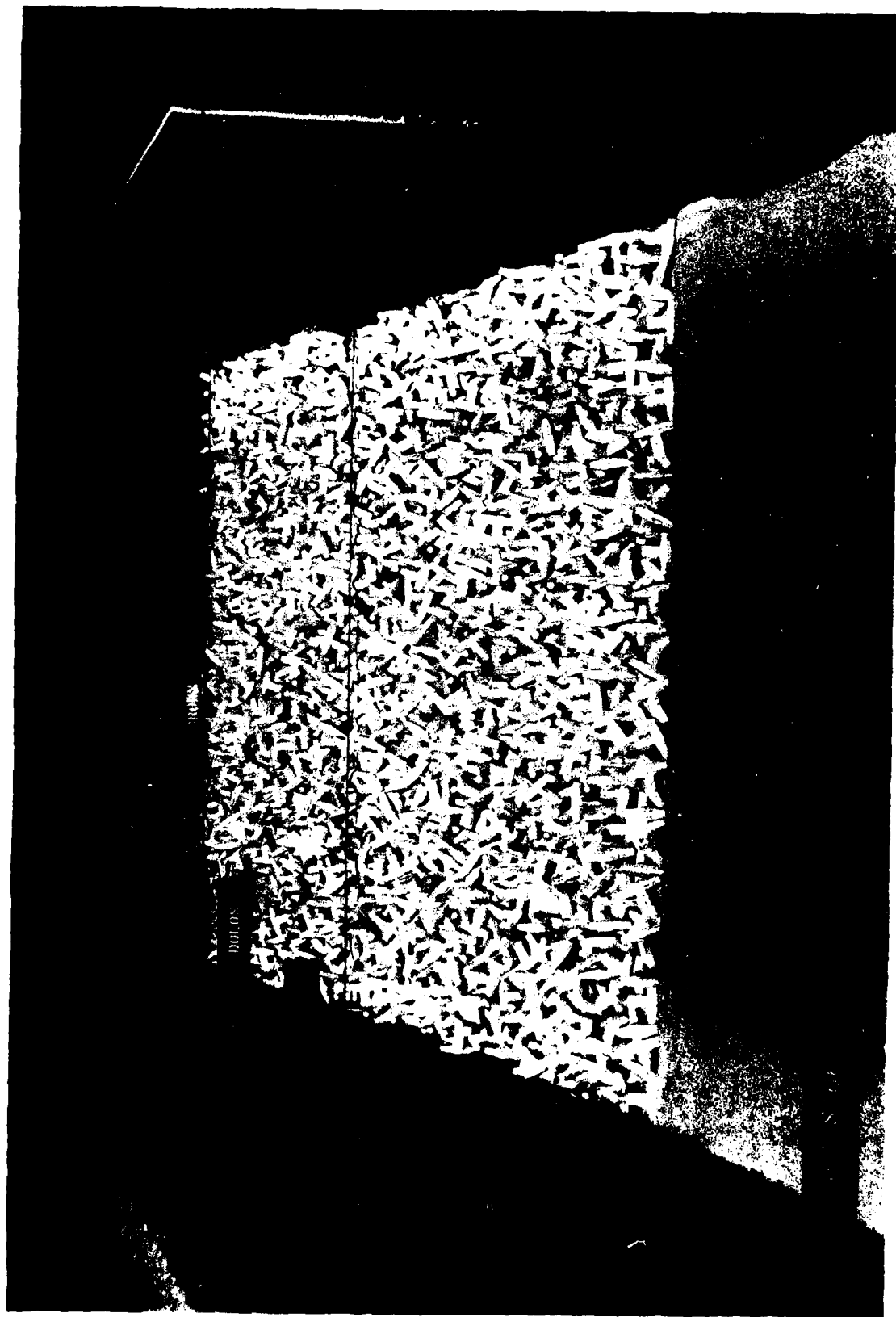


Photo 62. Sea-side view after attack of 1.52-sec, 0.64-ft waves;  $d = 0.90$  ft;  $w_a = 0.276$  lb;  
IV-on-3H structure slope; dolos armor

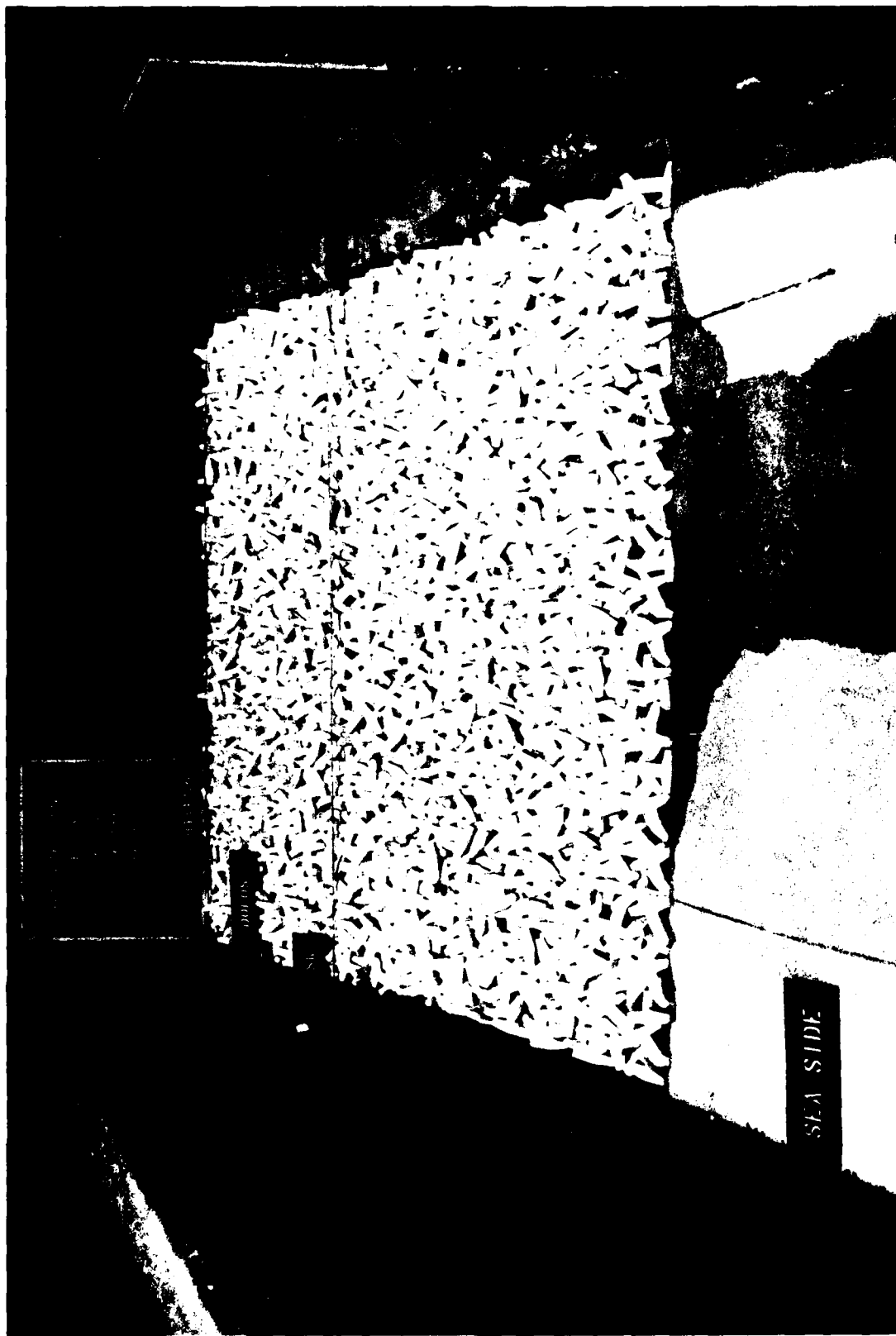
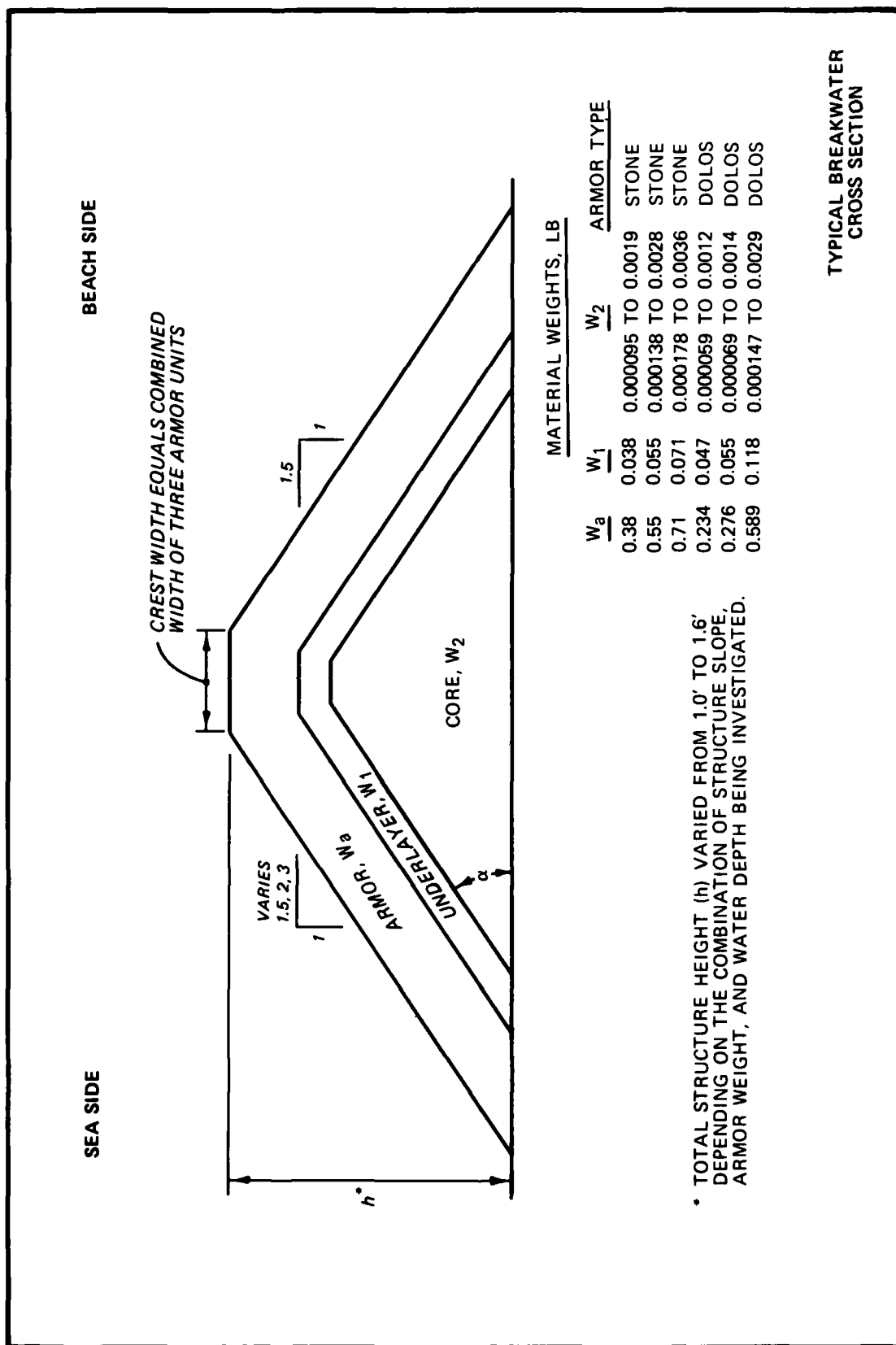
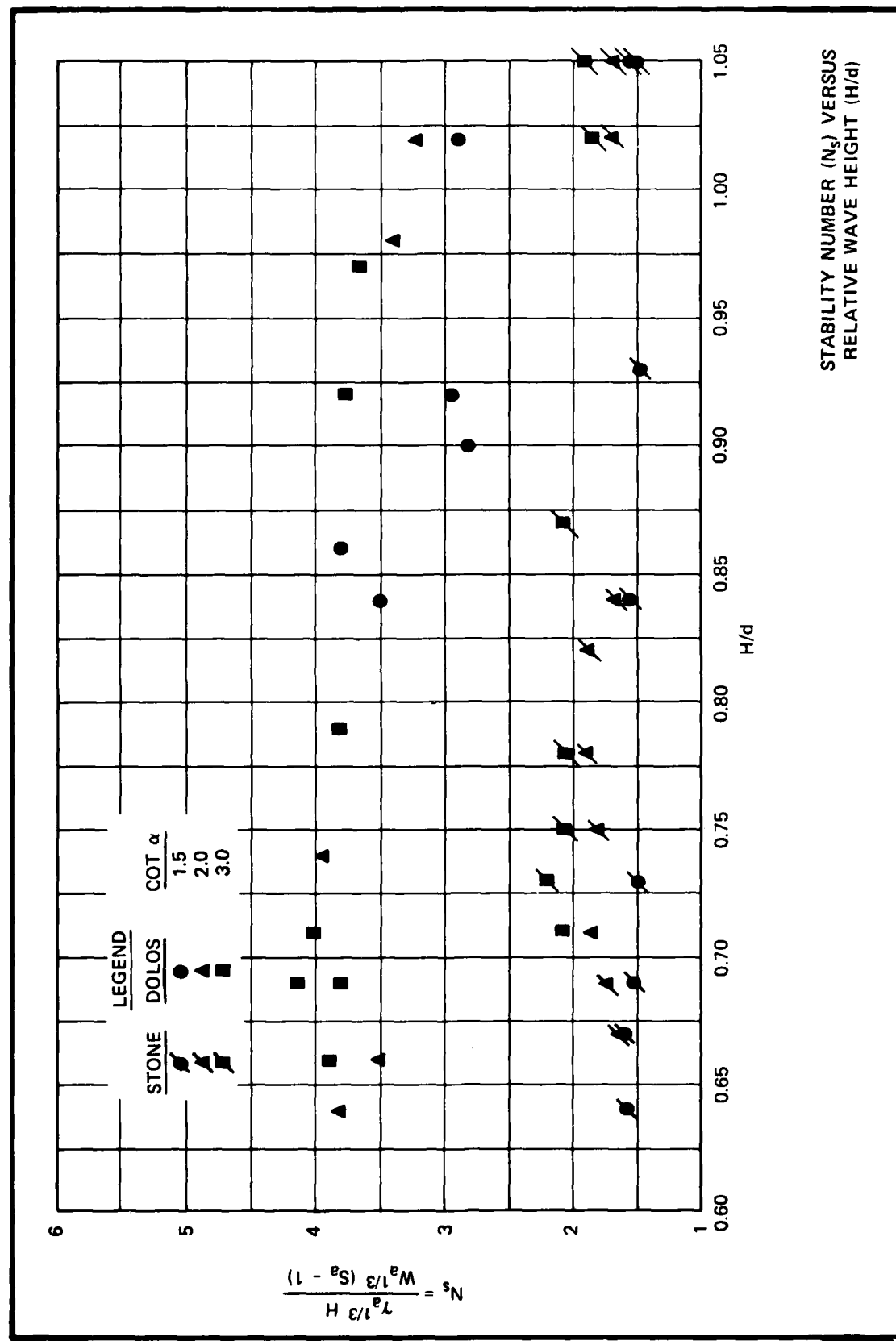


Photo 63. Sea-side view after attack of 1.56-sec, 0.66-ft waves;  $d = 0.95$  ft;  $W_a = 0.276$  lb;  
IV-on-3H structure slope; dolos armor



\* TOTAL STRUCTURE HEIGHT ( $h$ ) VARIED FROM 1.0' TO 1.6' DEPENDING ON THE COMBINATION OF STRUCTURE SLOPE, ARMOR WEIGHT, AND WATER DEPTH BEING INVESTIGATED.

PLATE 2



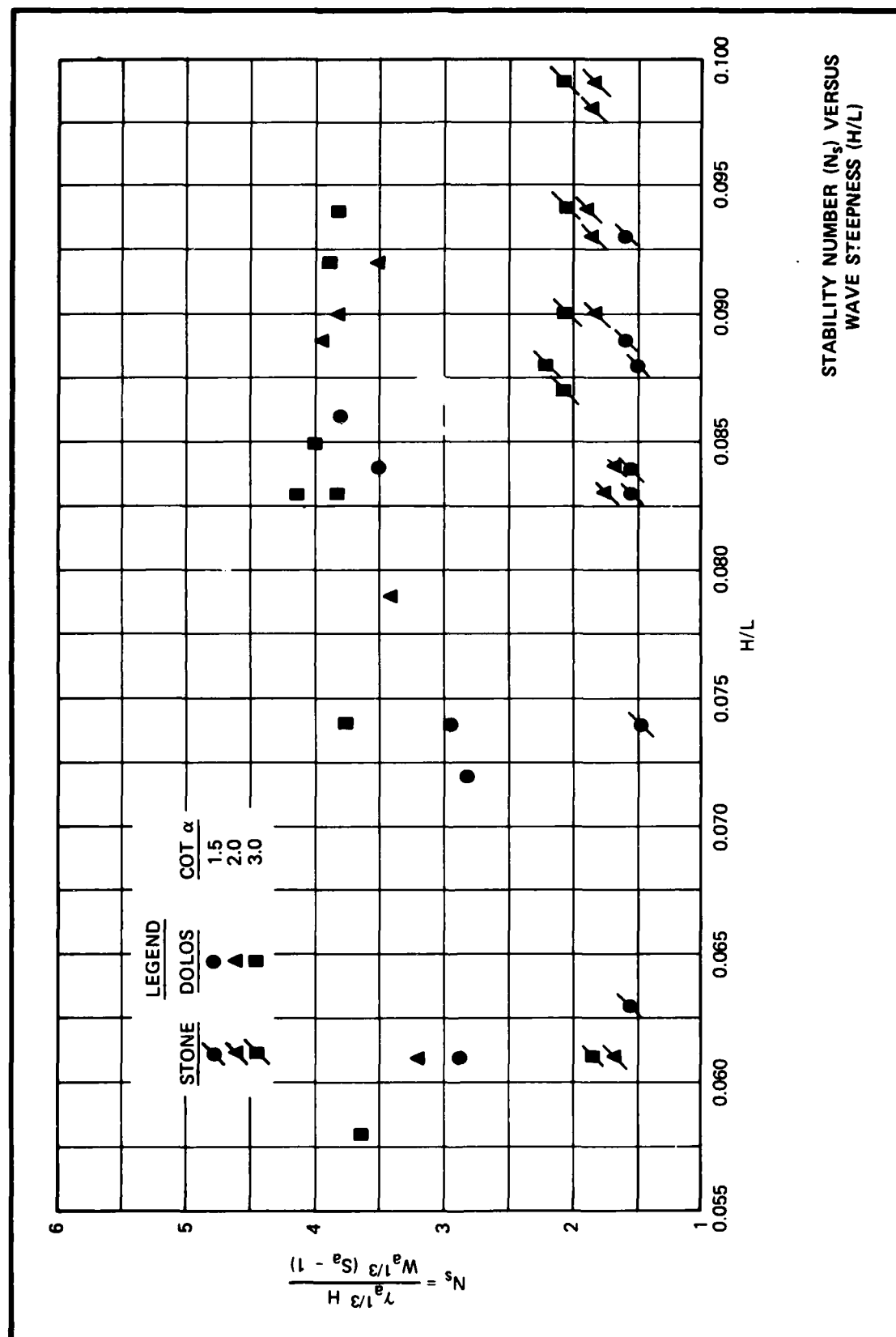


PLATE 3

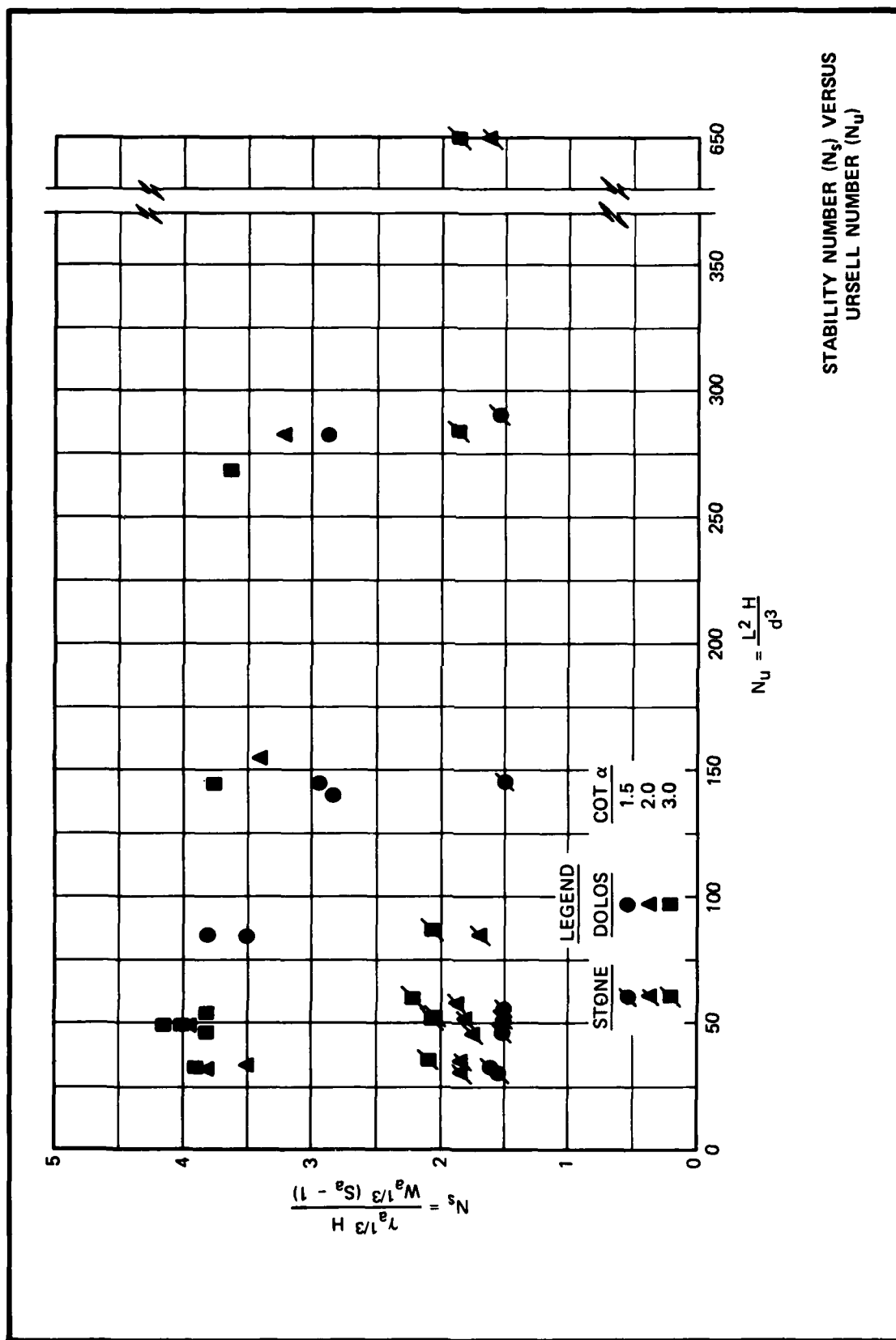
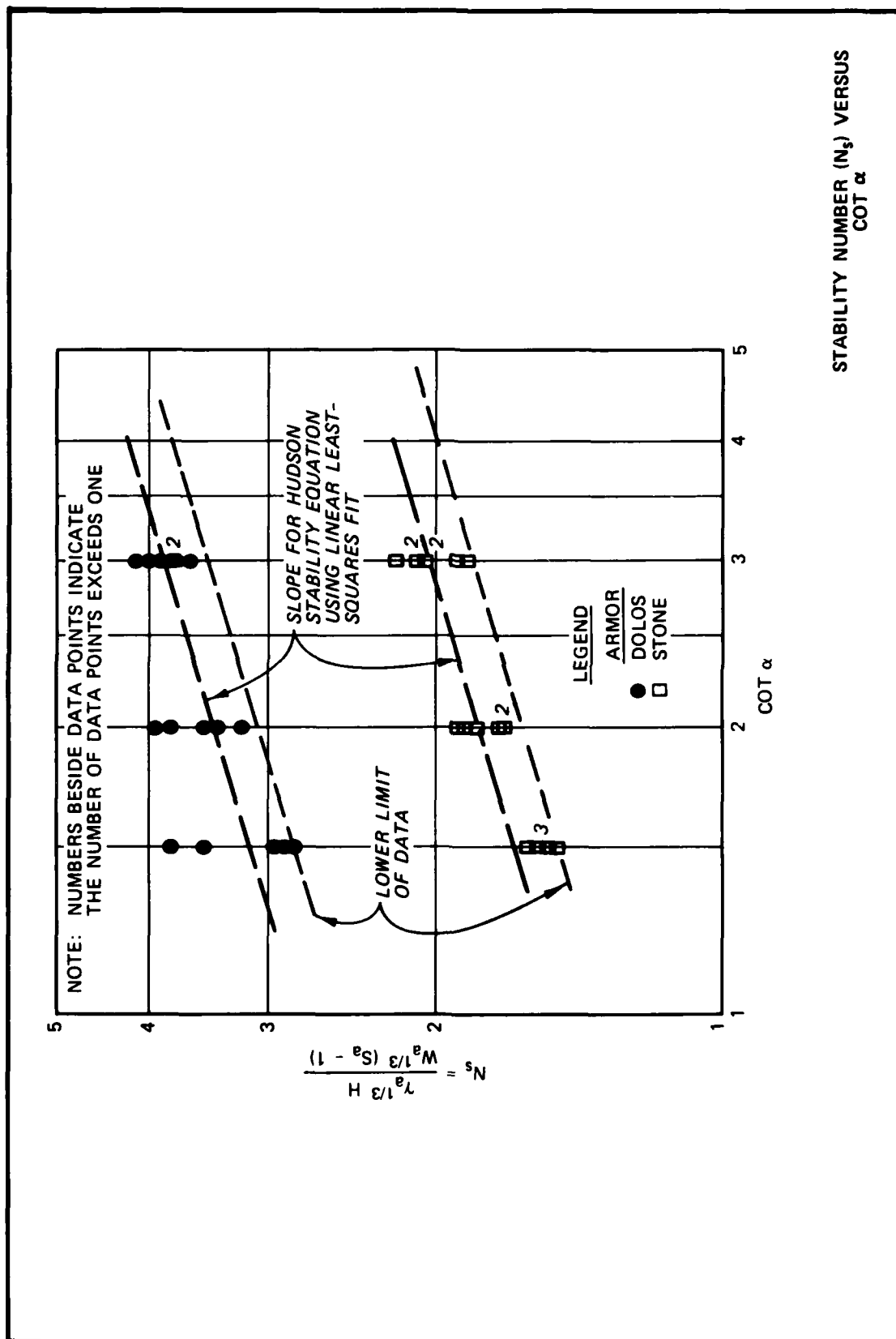


PLATE 4



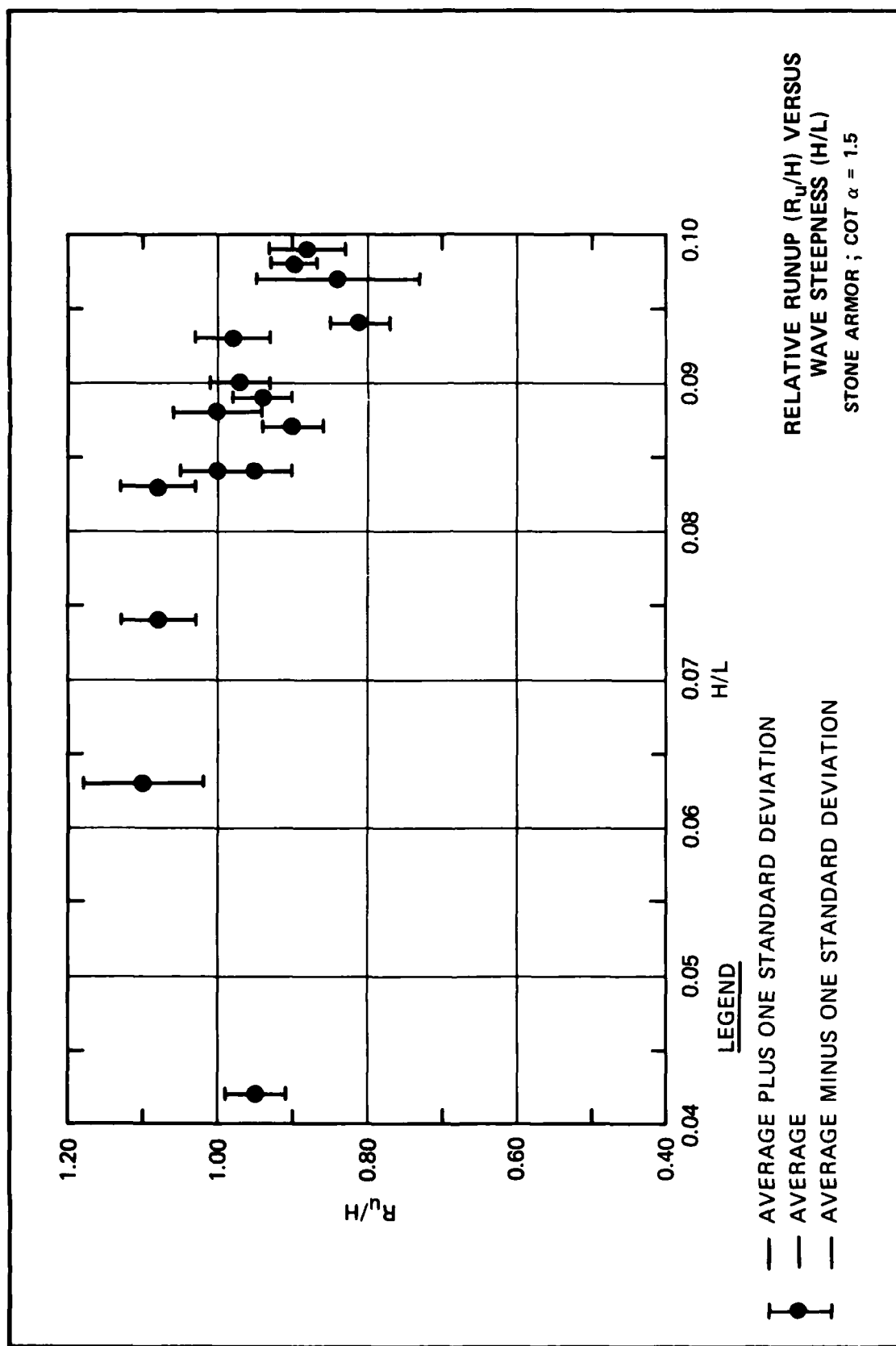
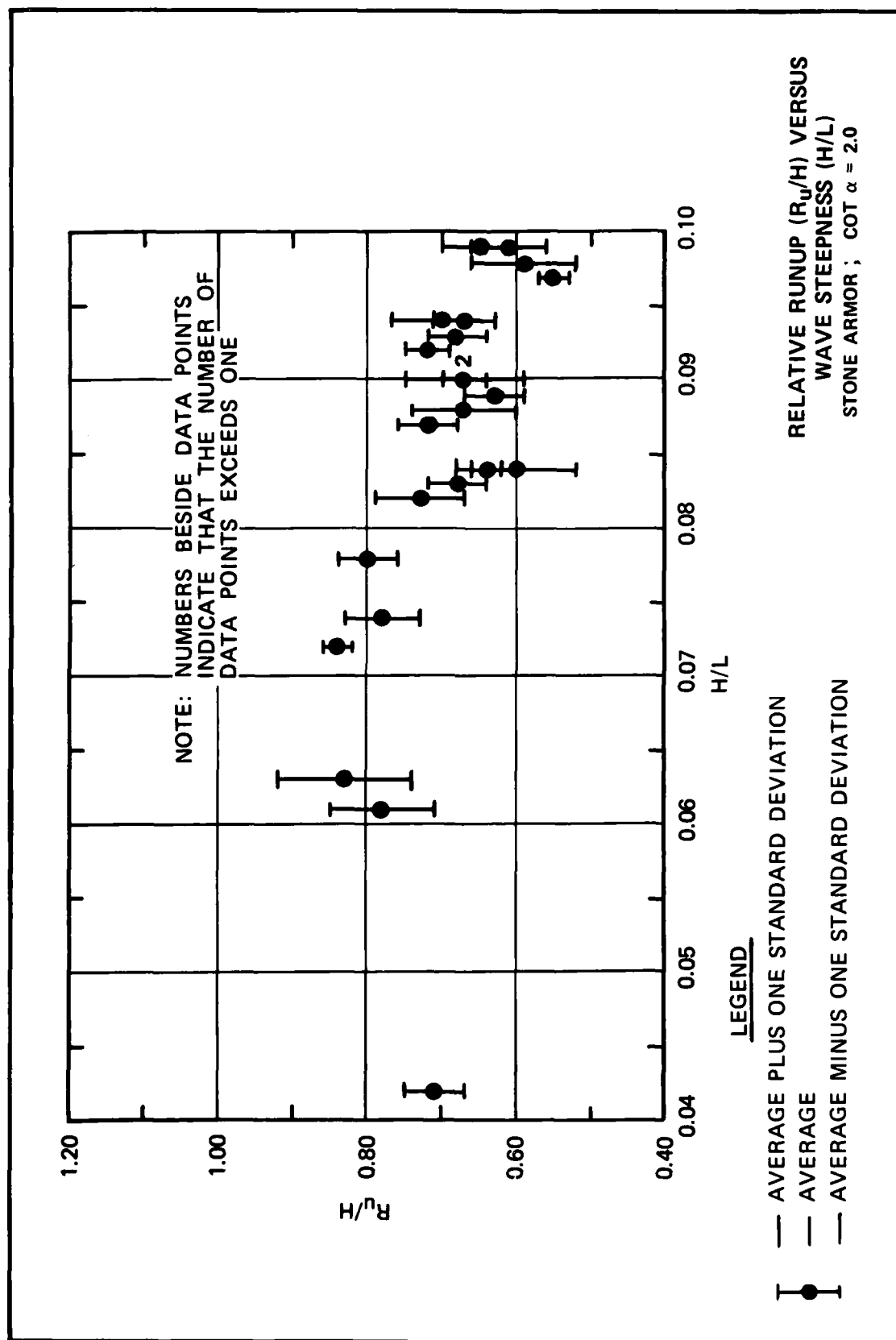
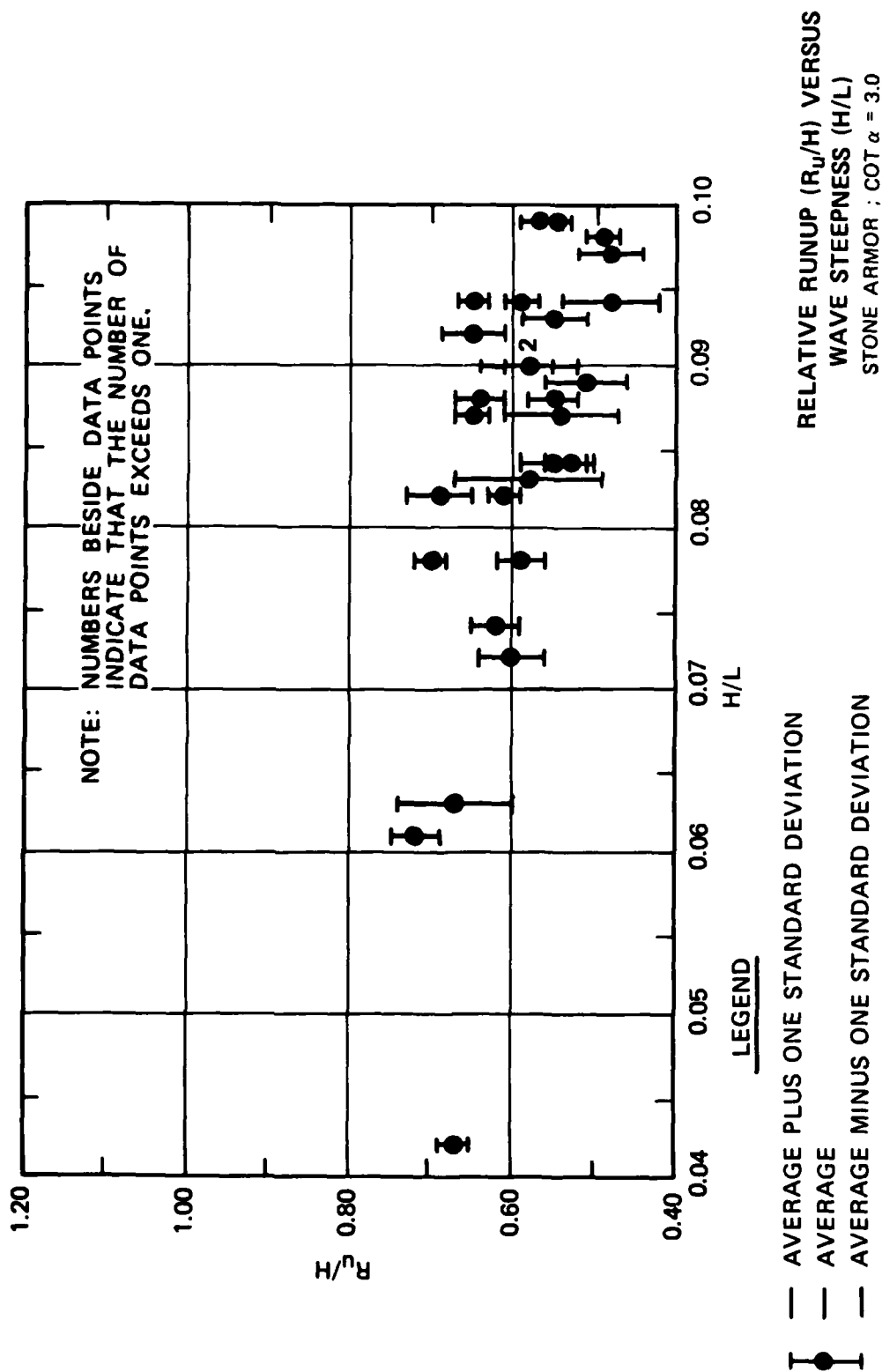
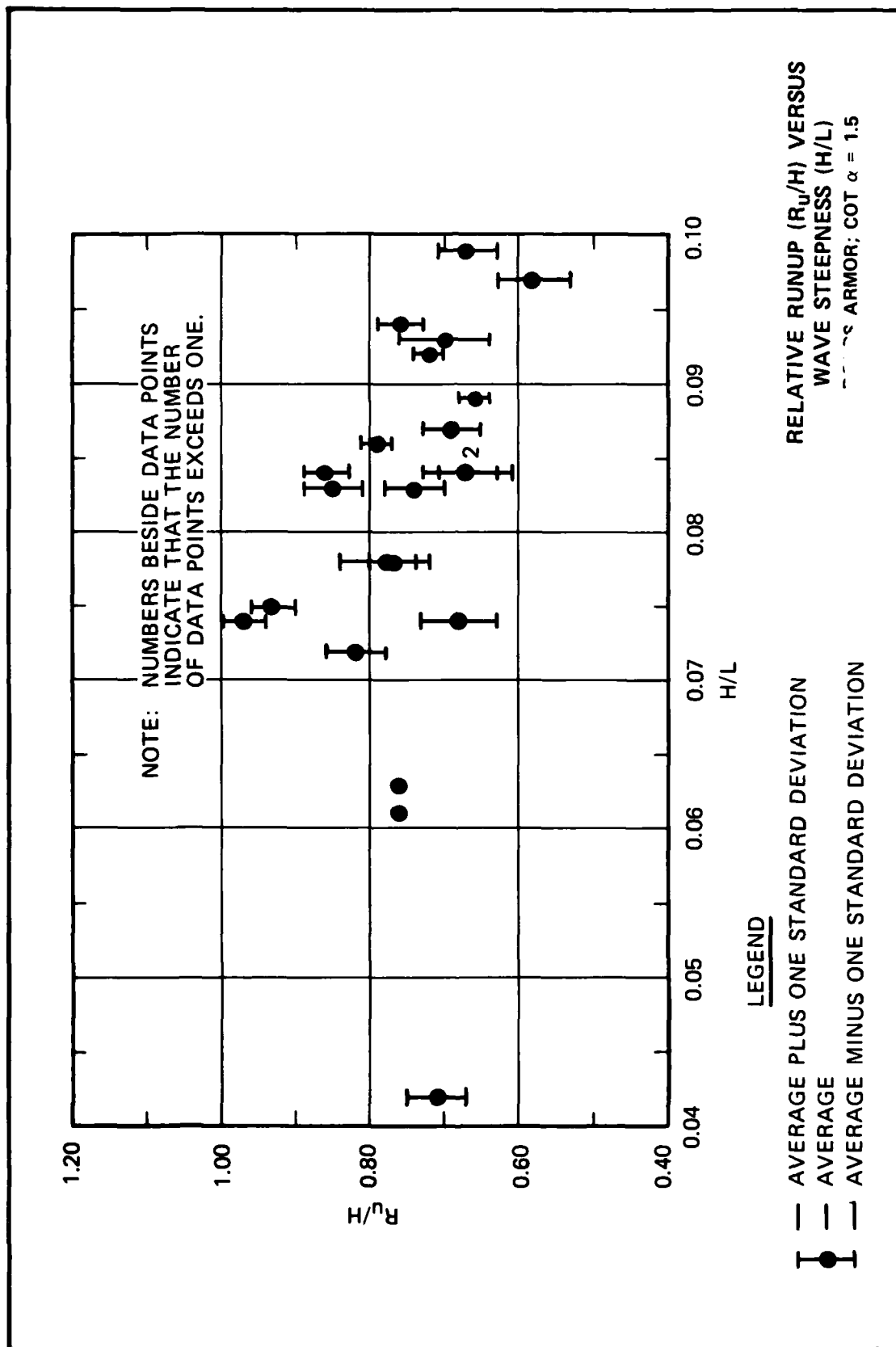
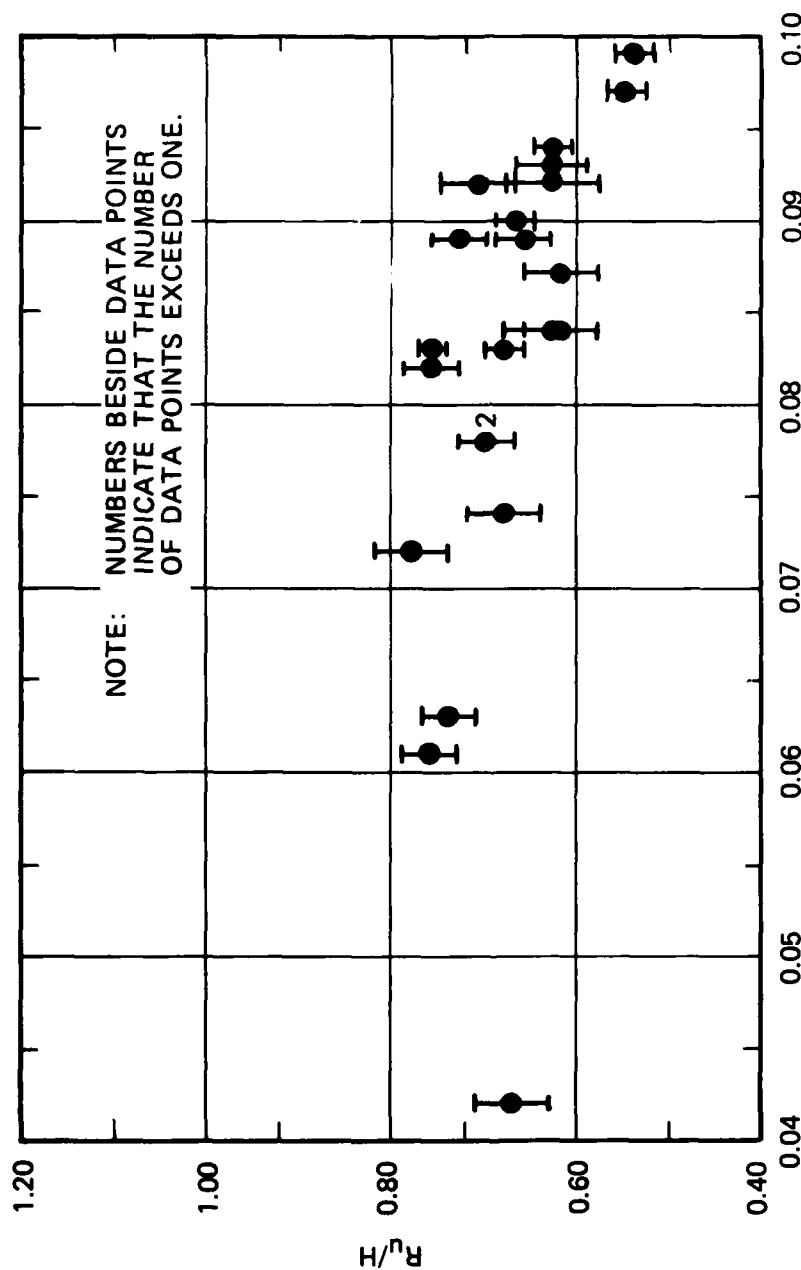


PLATE 6





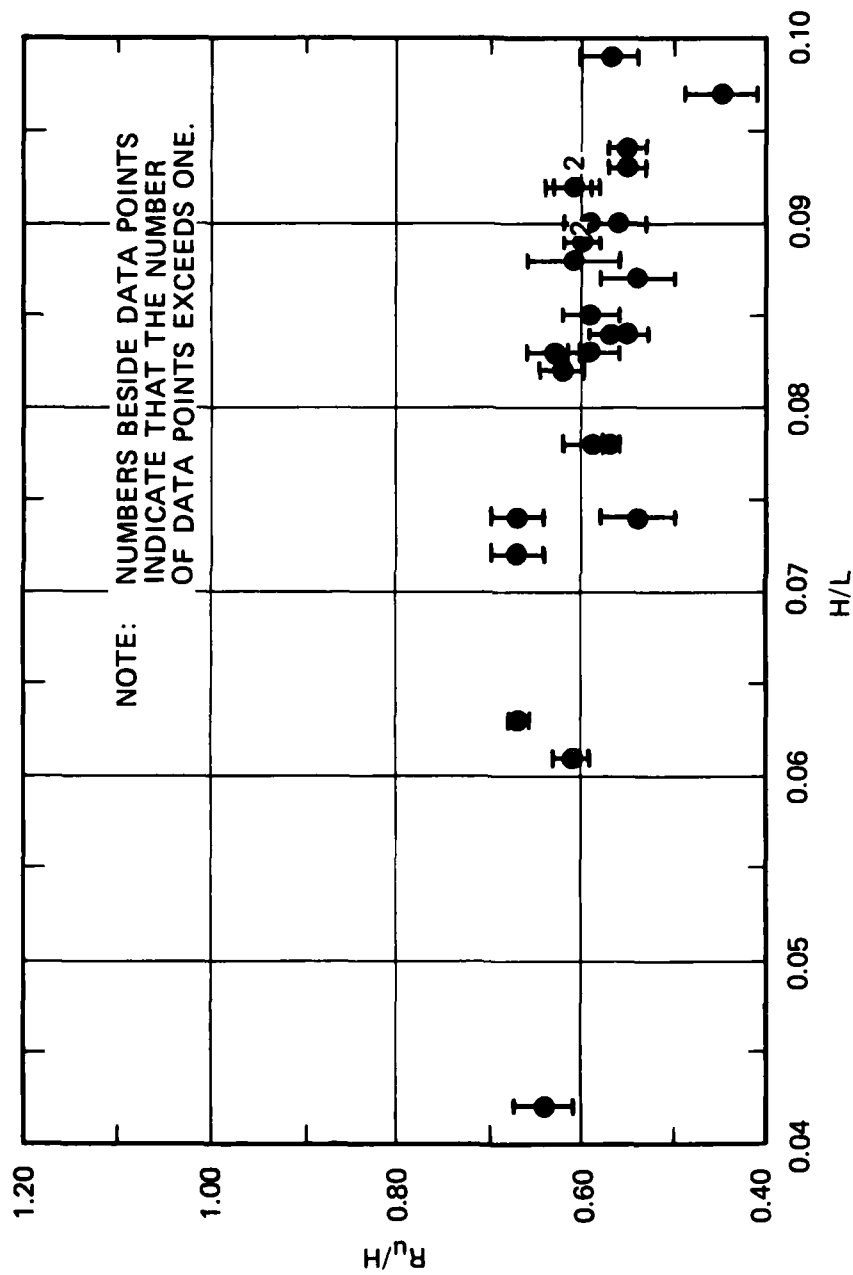




LEGEND

- AVERAGE PLUS ONE STANDARD DEVIATION
- AVERAGE
- AVERAGE MINUS ONE STANDARD DEVIATION

RELATIVE RUNUP ( $R_u/H$ ) VERSUS  
WAVE STEEPNESS ( $H/L$ )  
DOLOS ARMOR;  $\cot \alpha = 2.0$



RELATIVE RUNUP ( $R_u/H$ ) VERSUS  
WAVE STEEPNESS ( $H/L$ )  
DOLOS ARMOR;  $\cot \alpha = 3.0$

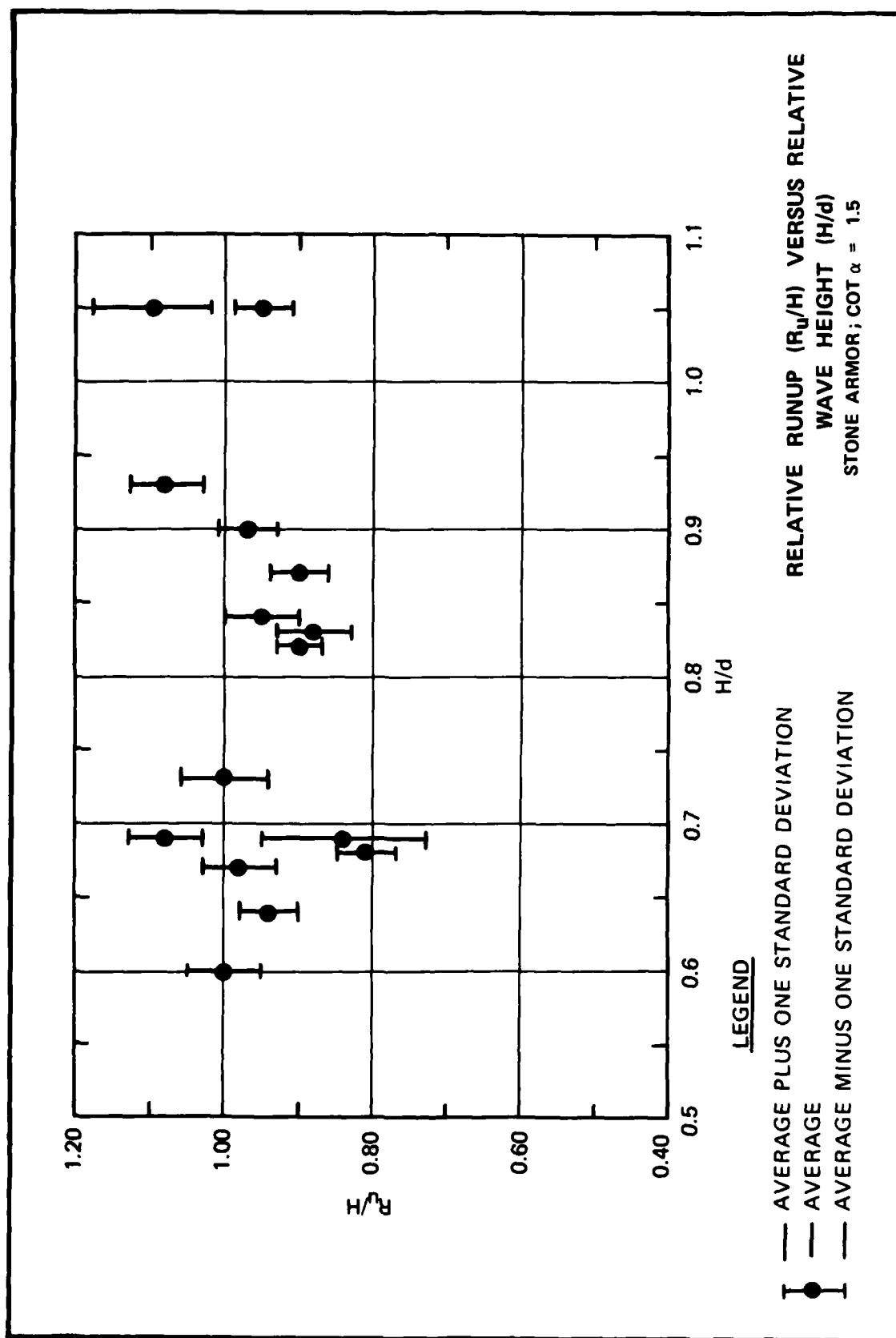
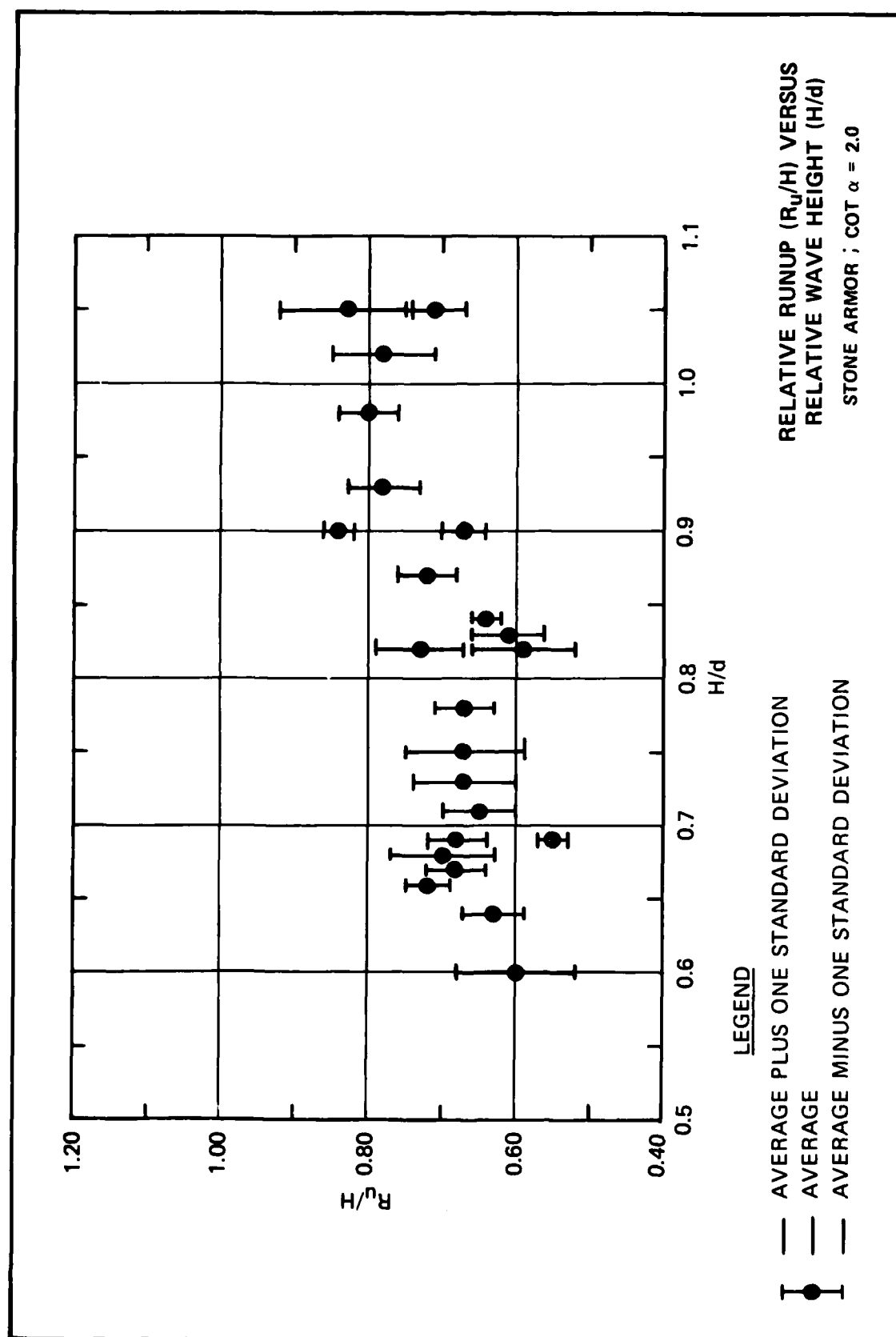


PLATE 12



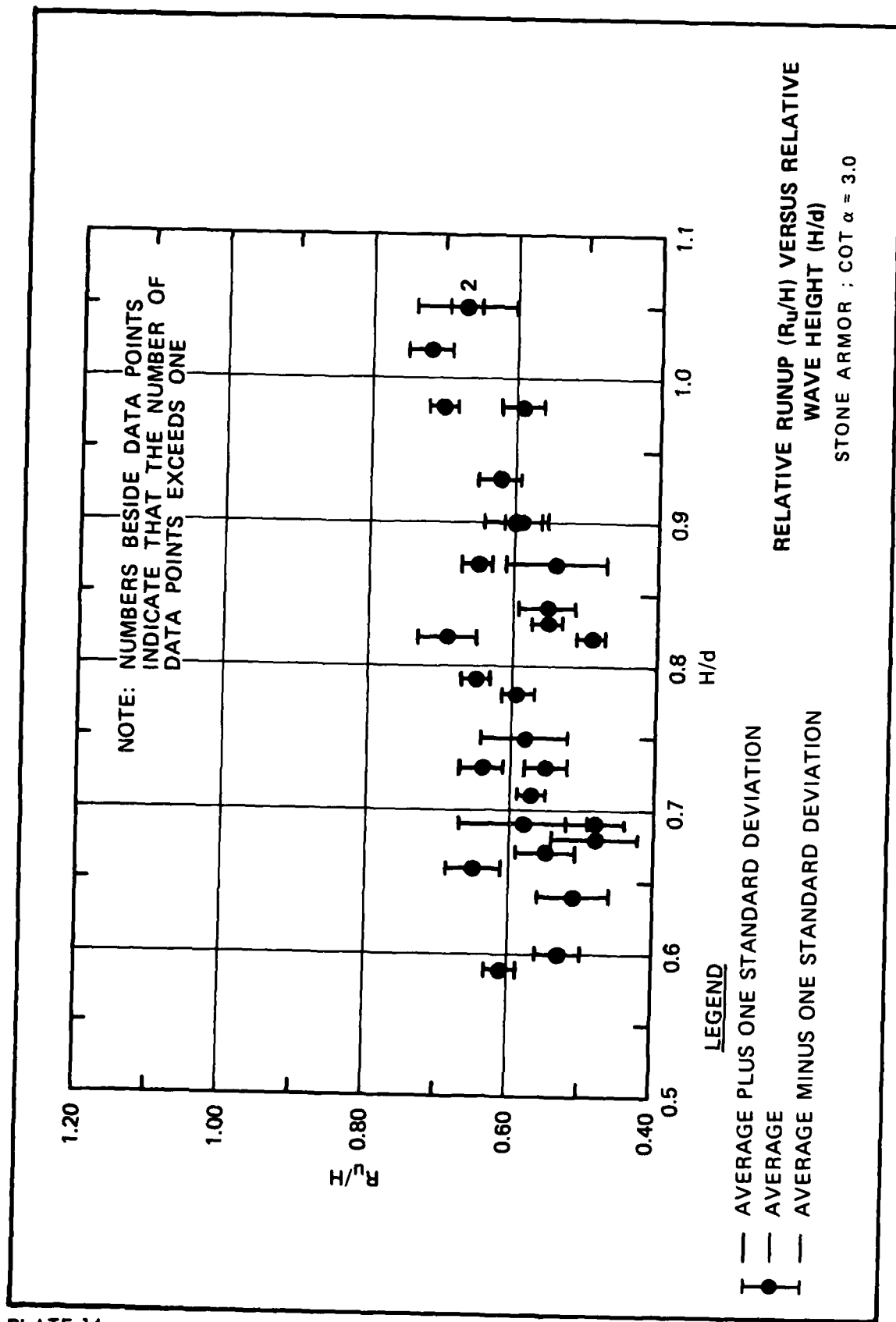
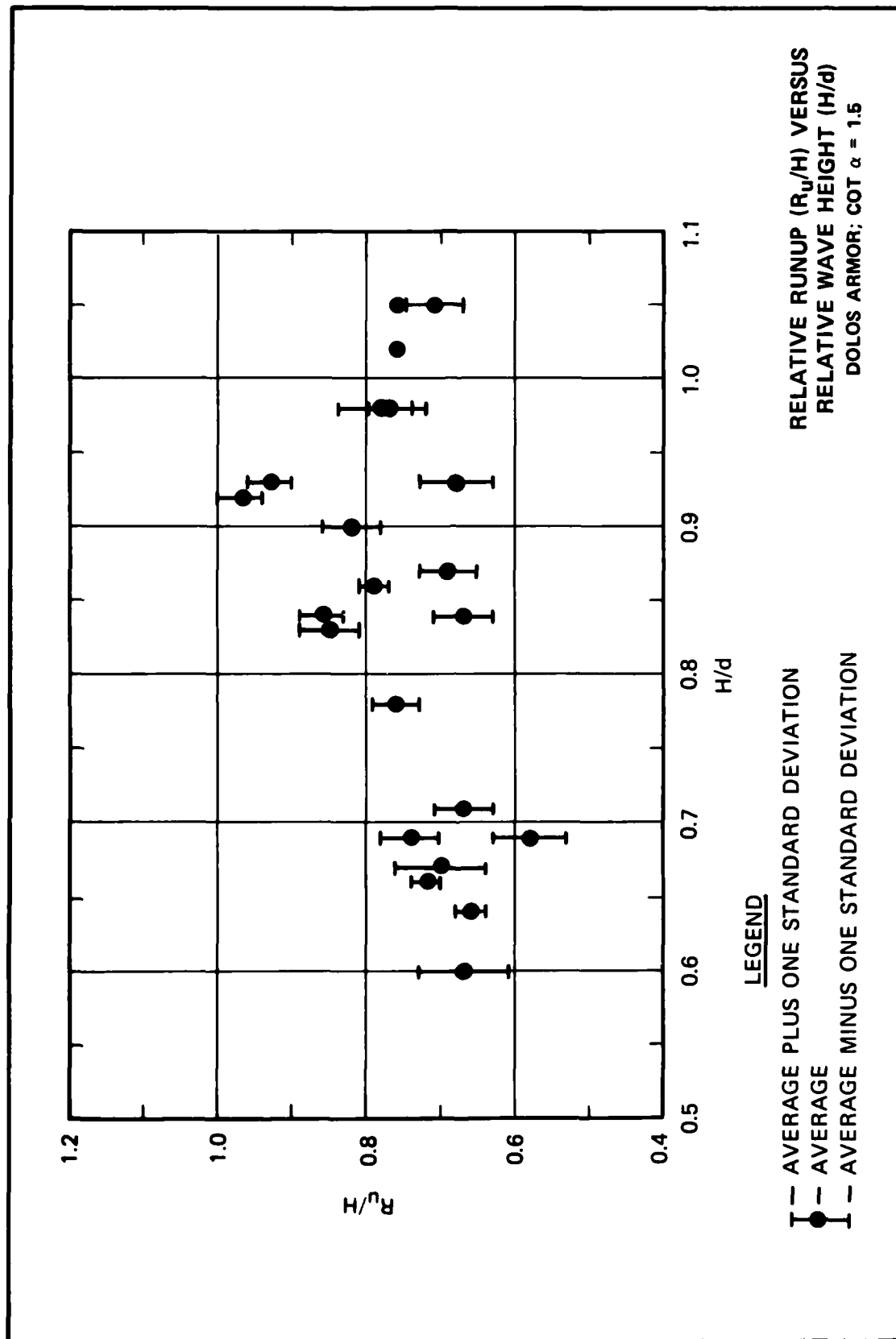
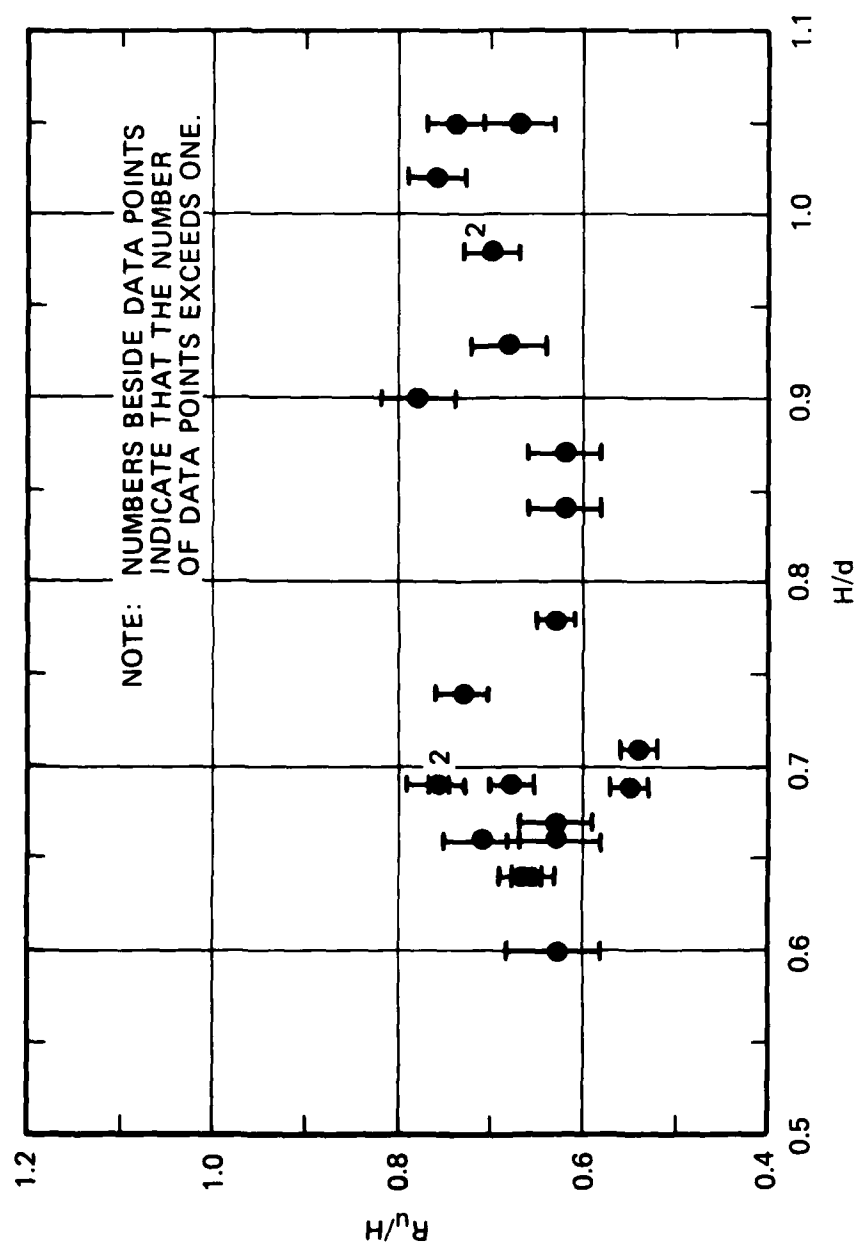


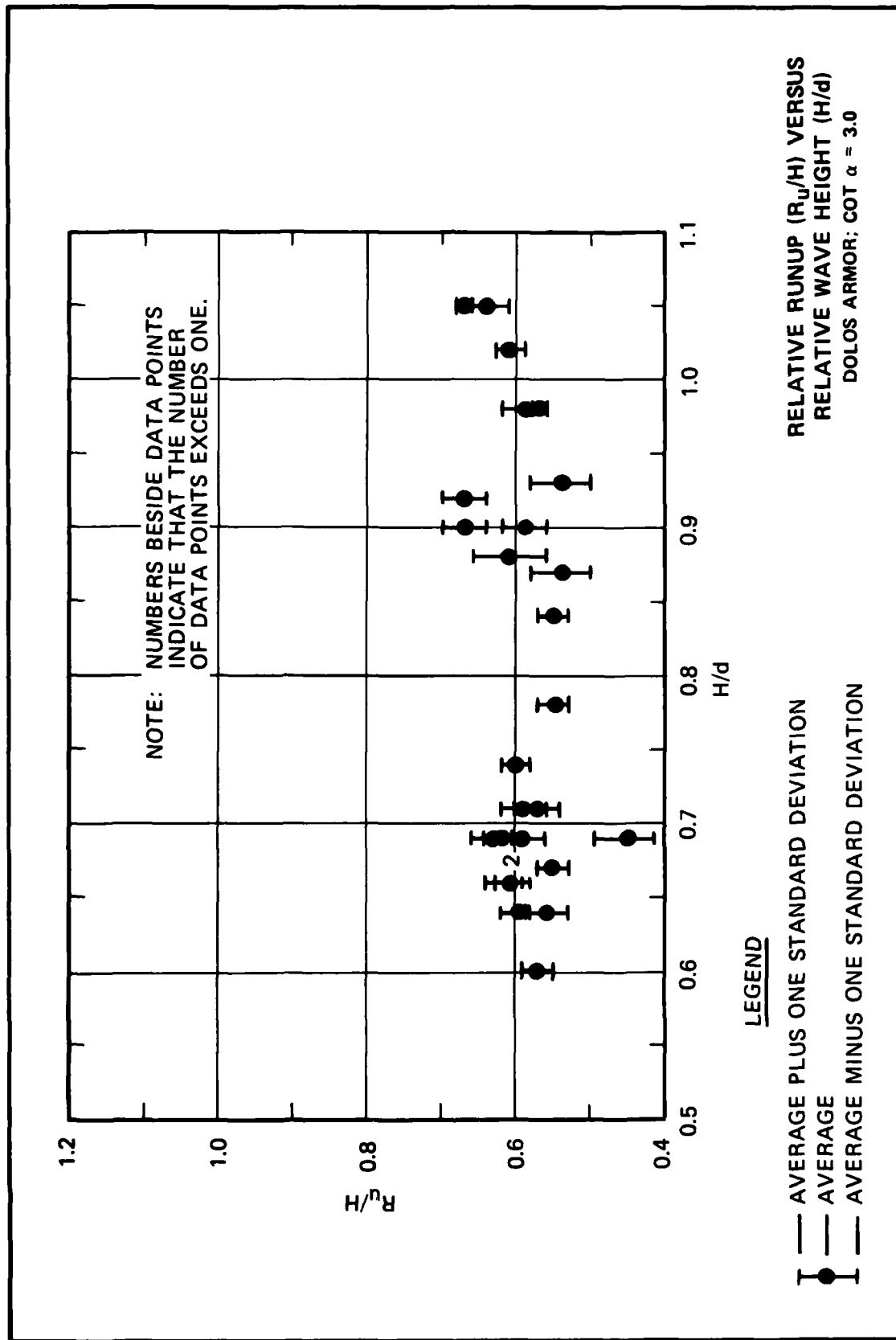
PLATE 14





RELATIVE RUNUP ( $R_u/H$ ) VERSUS  
RELATIVE WAVE HEIGHT ( $H/d$ )  
DOLOS ARMOR;  $\cot \alpha = 2.0$

— AVERAGE PLUS ONE STANDARD DEVIATION  
— AVERAGE  
— AVERAGE MINUS ONE STANDARD DEVIATION



# APPENDIX A: NOTATION

A	Surface area, $\text{ft}^2$
d	Water depth, ft
d/L	Relative depth
D	Damage parameter Reads "function of"
F	Force
g	Acceleration due to gravity, $\text{ft}/\text{sec}^2$
h	Height of breakwater crown, ft
H	Wave height, ft
H/d	Relative wave height
H/L	Wave steepness
$k_\Delta$	Shape coefficient
$K_D$	Stability coefficient
$\ell_a$	Characteristic length of armor unit, ft
L	Length, wavelength, ft
n	Number of layers of armor units
N	Number of armor units
$N_u$	Ursell Number = $(L^2 H/d^3)$
P	Porosity of breakwater material, percent
PT	Placement technique
$R_N$	Reynolds stability number = $(g^{1/2} H^{1/2} \ell_a)/\nu$
$R_u/H$	Relative runup
$R_u$	Wave runup measured vertically above swl, ft
$S_a$	Specific gravity of an armor unit relative to water in which the breakwater is constructed
T	Wave period, sec; time
W	Weight, lb
$\alpha$	Angle of breakwater slope, measured from horizontal, deg
$\cot \alpha$	Reciprocal of breakwater slope
$\beta$	Angle of wave attack, deg
$\gamma$	Specific weight, pcf
$\gamma_a$	Specific weight of an armor unit, pcf
$\Delta$	Shape of armor unit or underlayer material

$\theta$  Angle between the horizontal and the sea bottom on which the breakwater is constructed

$\nu$  Kinematic viscosity

Subscripts

a Refers to armor unit

s Refers to stability

w Refers to water in which the structure is located

1 and 2 Refers to underlayer and core, respectively

END

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